Probing Growth with CMB Lensing

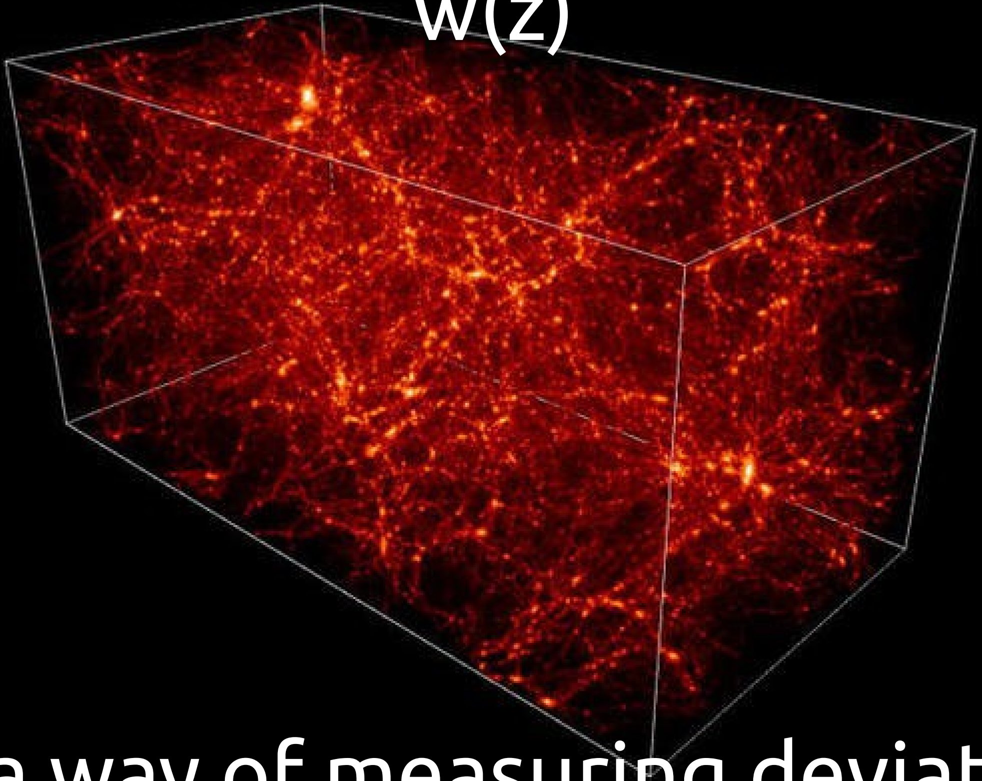
Cluster Counts and Cross-Correlations

Mathew Madhavacheril

Outline

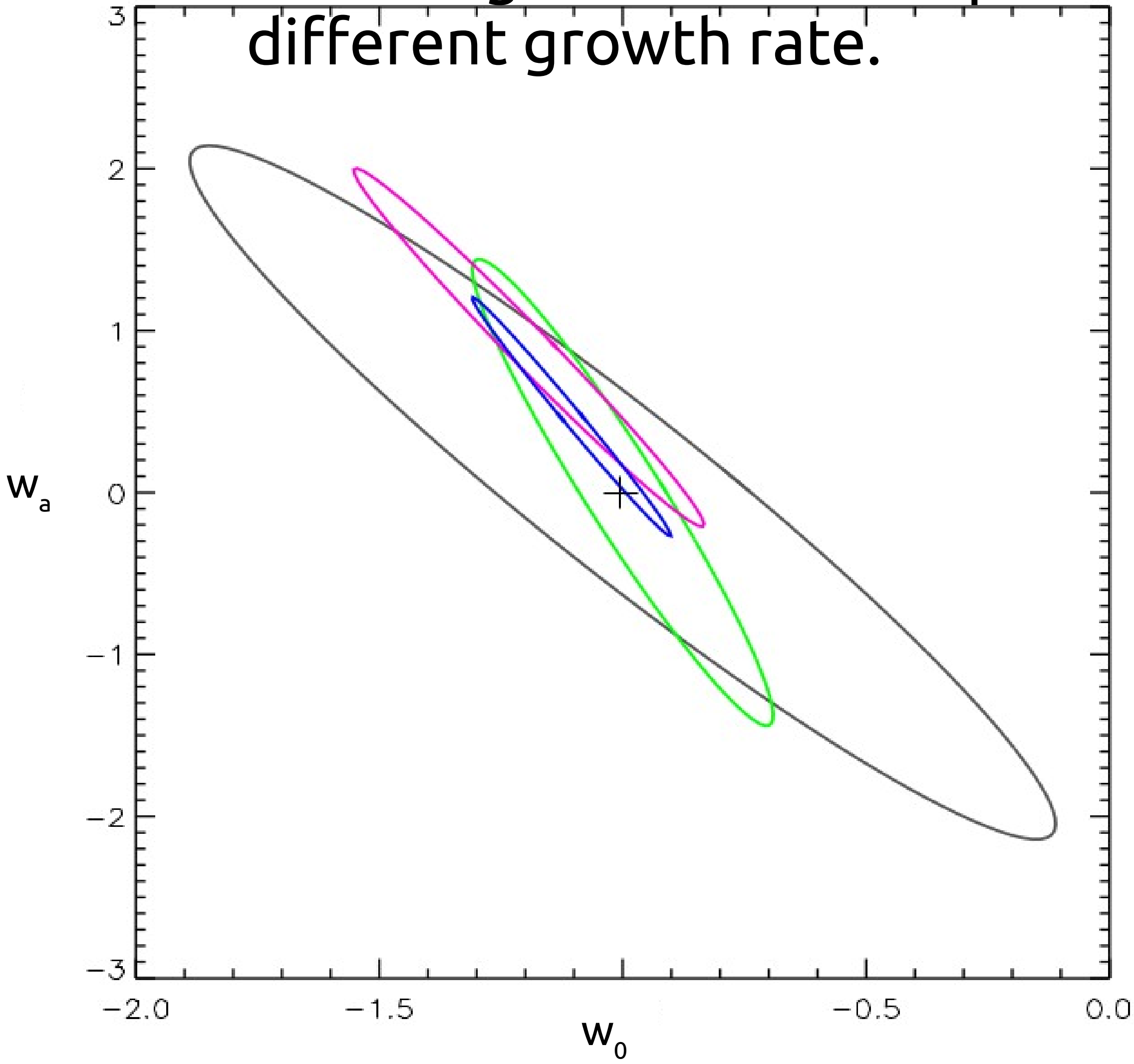
- Dark Energy and Modified Gravity: growth probes complement expansion probes
  - Hints of discrepancies post-Planck
- Cluster counting for growth with SZ + optical and CMB halo lensing(CMBHL)
  - A first detection by ACTPol of CMBHL
  - Measurements by Planck and SPTPol
  - Prospects and challenges for CMBHL
- Cross-correlations for growth and bias calibration

Clustering of matter (growth of structure) is sensitive to the Dark Energy equation of state w(z)



This offers a way of measuring deviations from Λ that is complementary to distance probes.

If Dark Energy is due to a breakdown of GR on large scales, it's possible for an alternative to give the same expansion rate but a different growth rate.



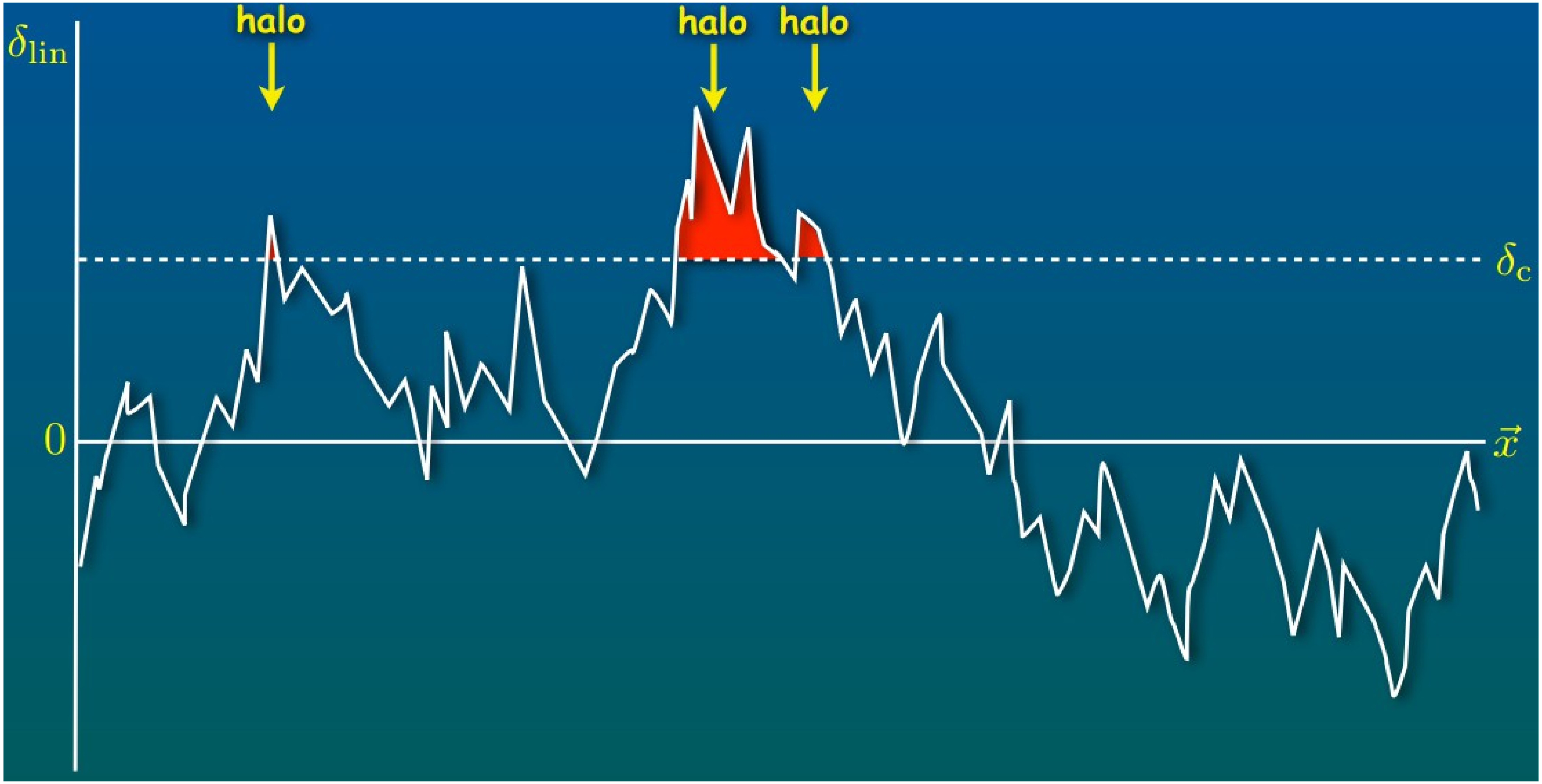
Shapiro, Dodelson, Hoyle, Samushia, Flaugher (1004.4810)

DES Projections

BAO
Supernovae
Cluster Counts
Weak Lensing

Expansion rate probes (e.g. BAO, SN) not enough to test all possibilities; we need to measure growth!

Halo abundance



$$\frac{dN}{dM\,dV} = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{1}{2}\frac{\delta_c^2}{\sigma^2}\right)\frac{\rho_M}{M}\frac{d\ln\sigma^{-1}}{dM}$$

Press,
Schechter,
1974

Halo abundance

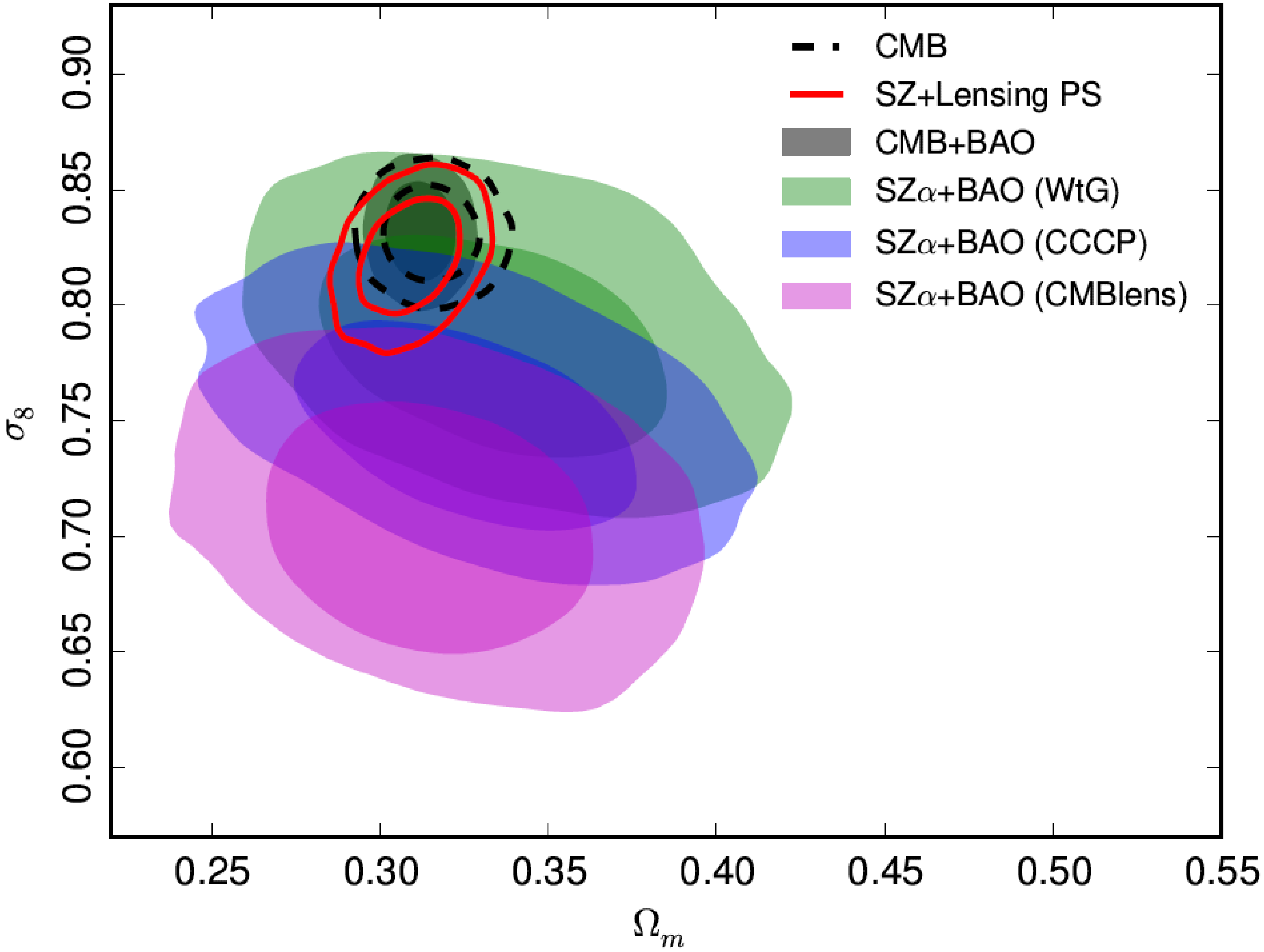
Measure halo abundance by measuring masses of clusters as a function of redshift

$$\frac{dN}{dM\,dV} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2}\frac{\delta_c^2}{\sigma^2}\right) \frac{\rho_M}{M} \frac{d\ln\sigma^{-1}}{dM}$$

Sensitive to $\sigma_8(z)$, use to constrain $w(z)$

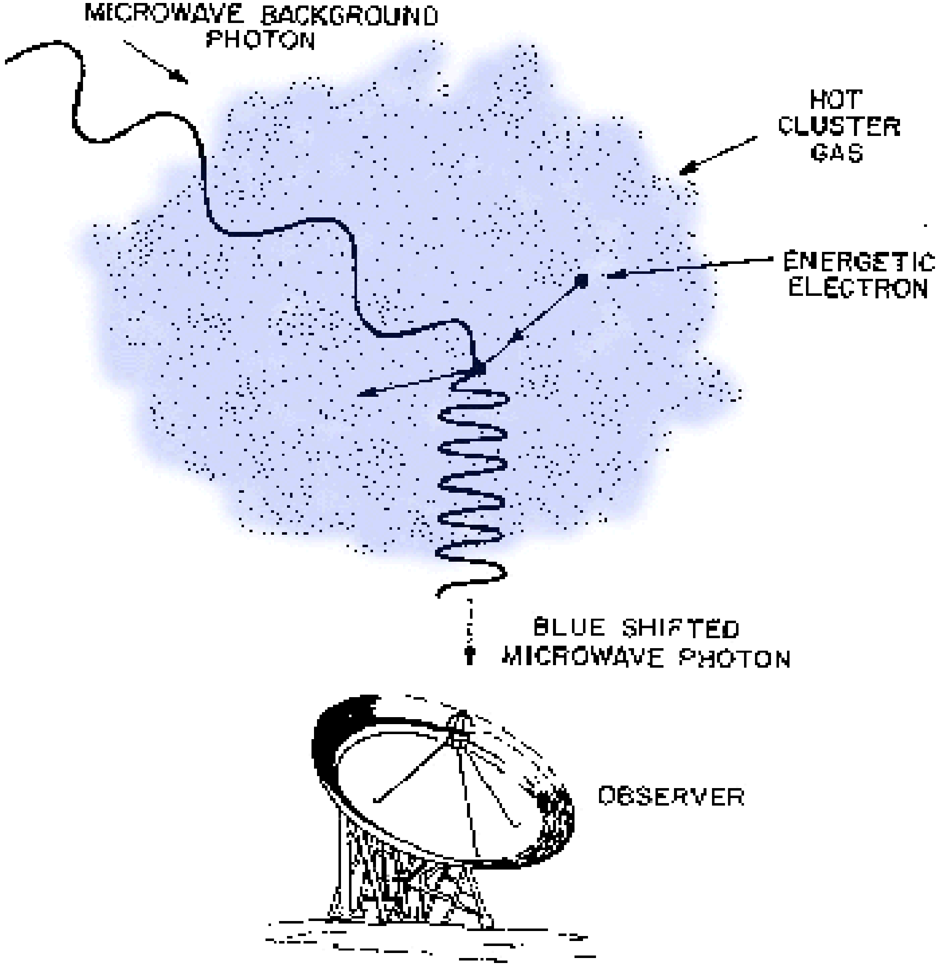
Planck

Tension between primary CMB and cluster counts

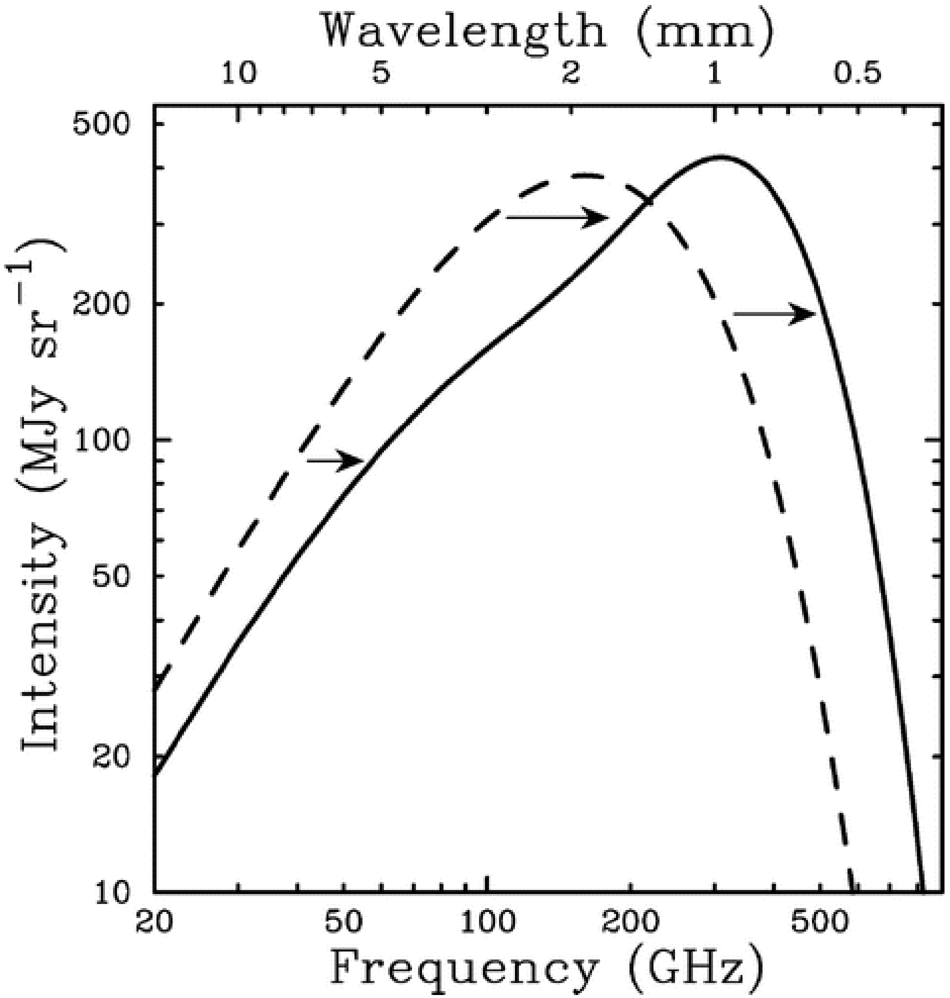


Step 1: Find halos

Sunyaev-Zel'dovich (SZ) effect



Sunyaev-Zel'dovich (SZ) effect



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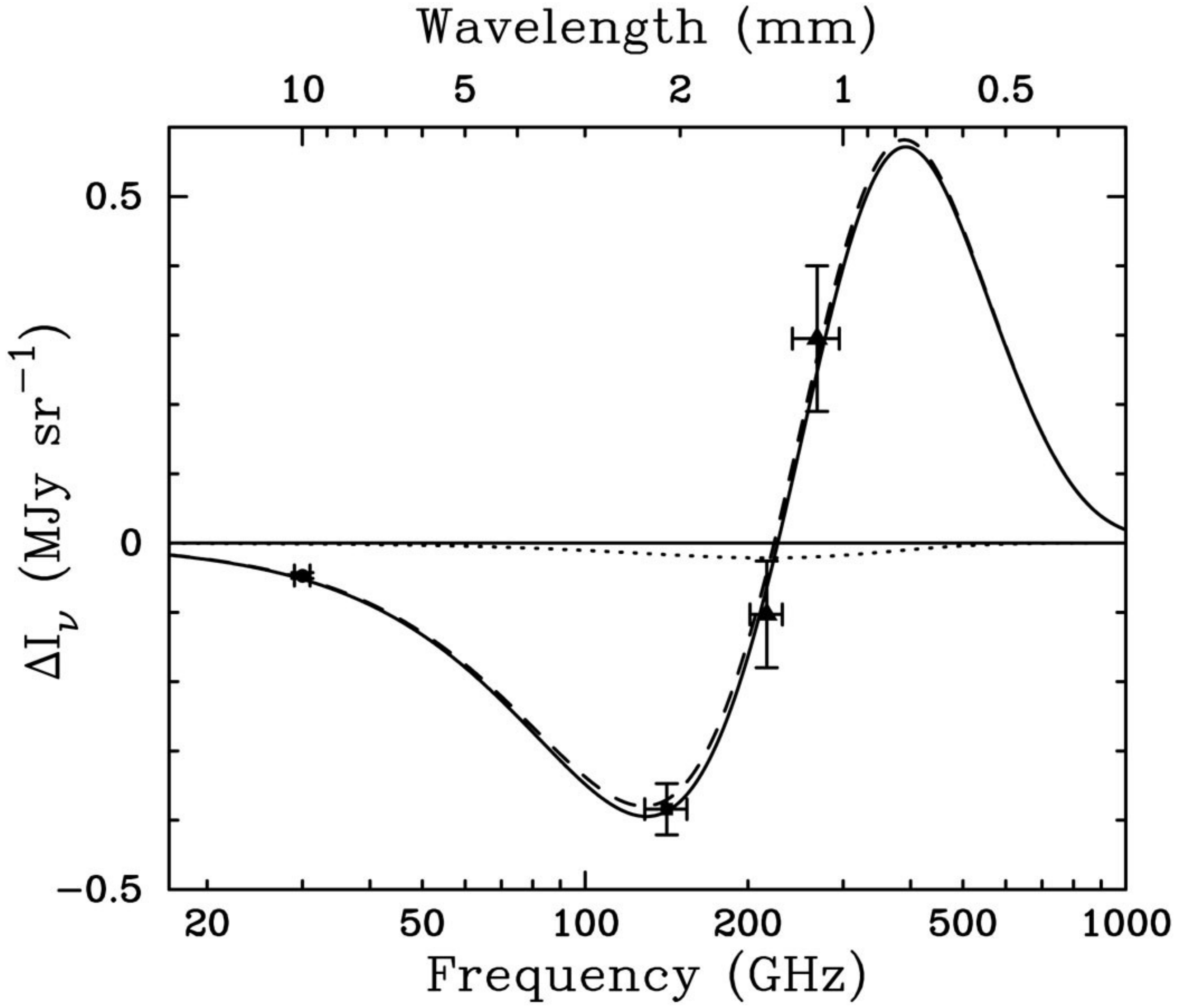

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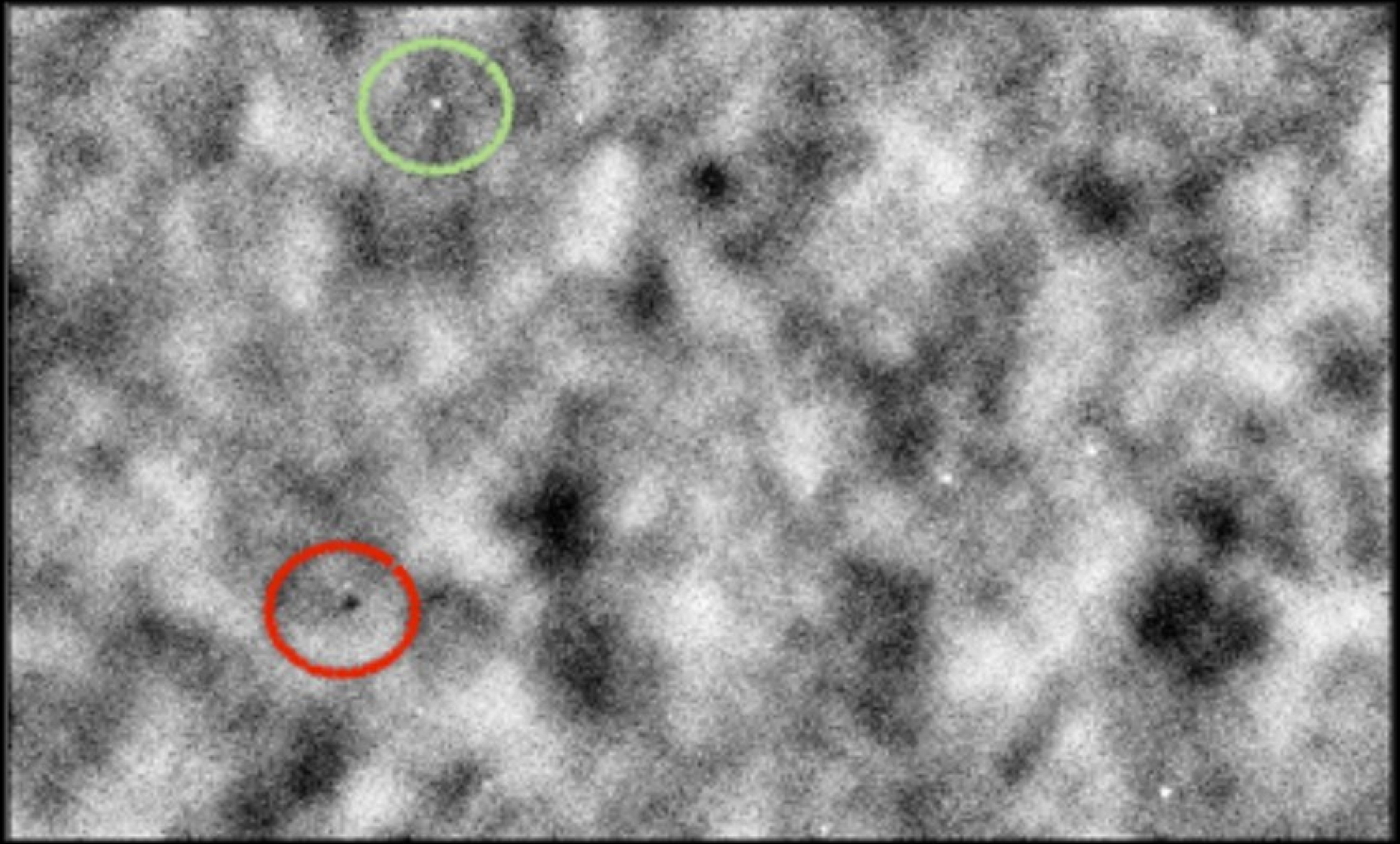
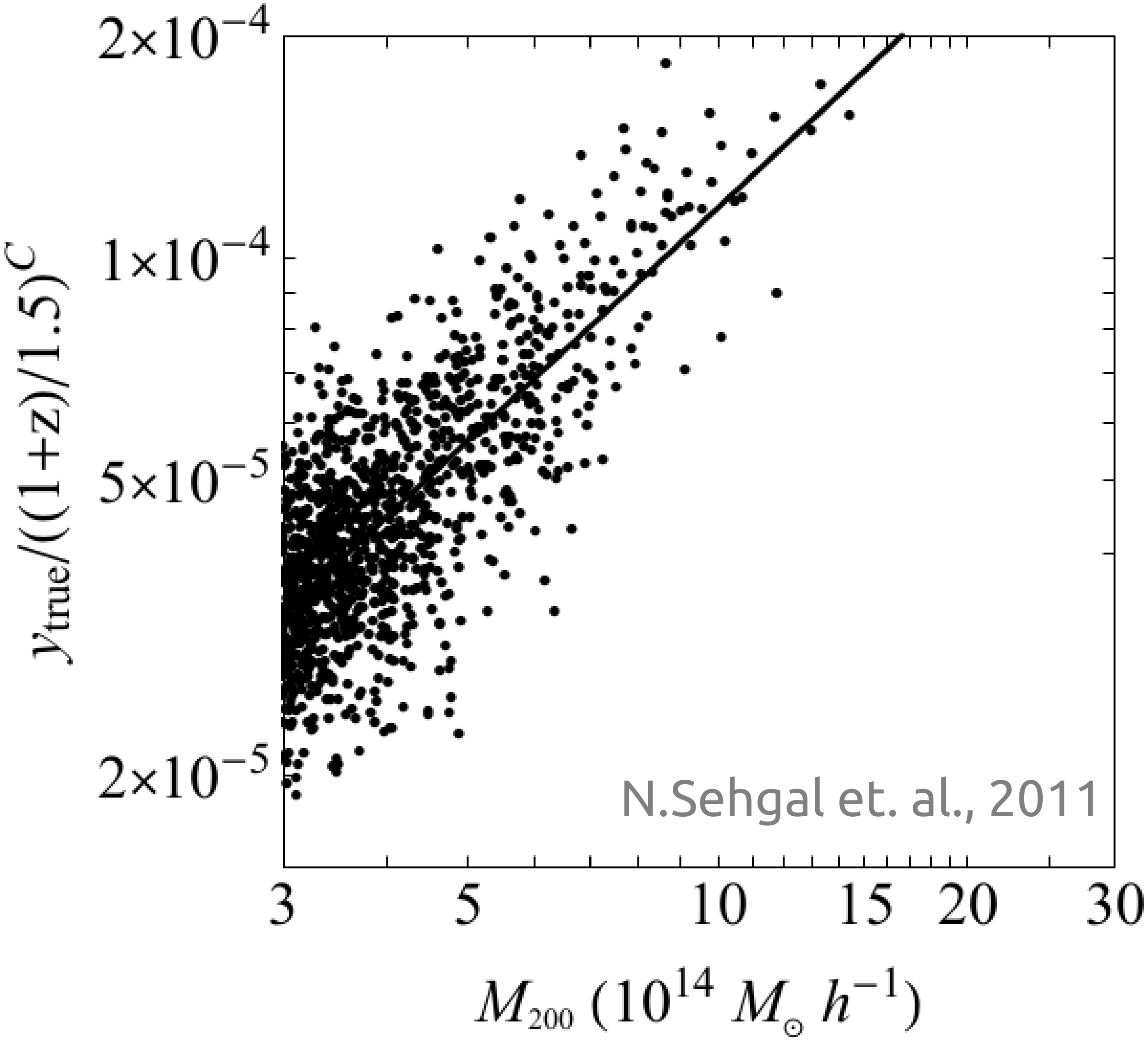


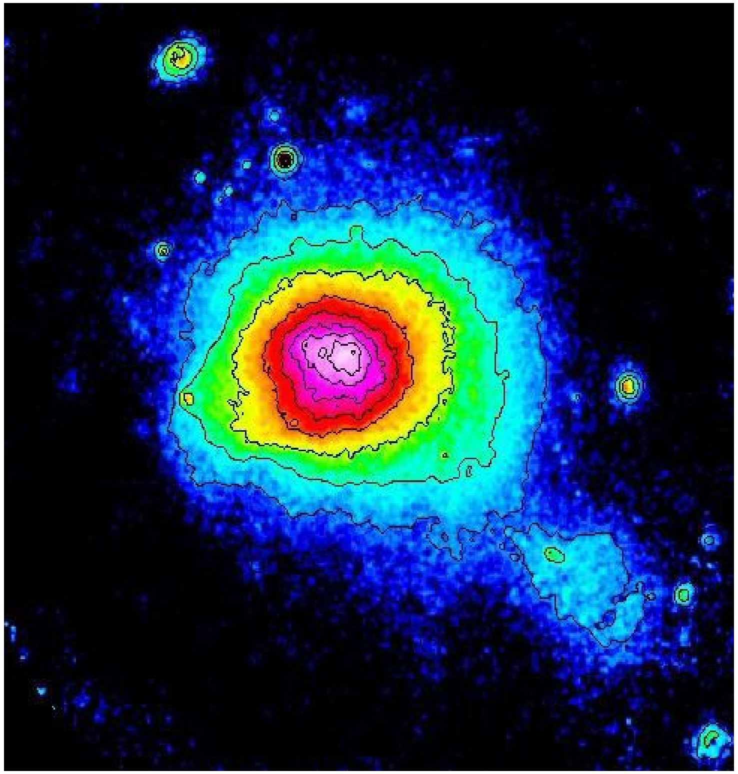
Amir Hajian for ACT

Significant scatter in decrement vs. true mass



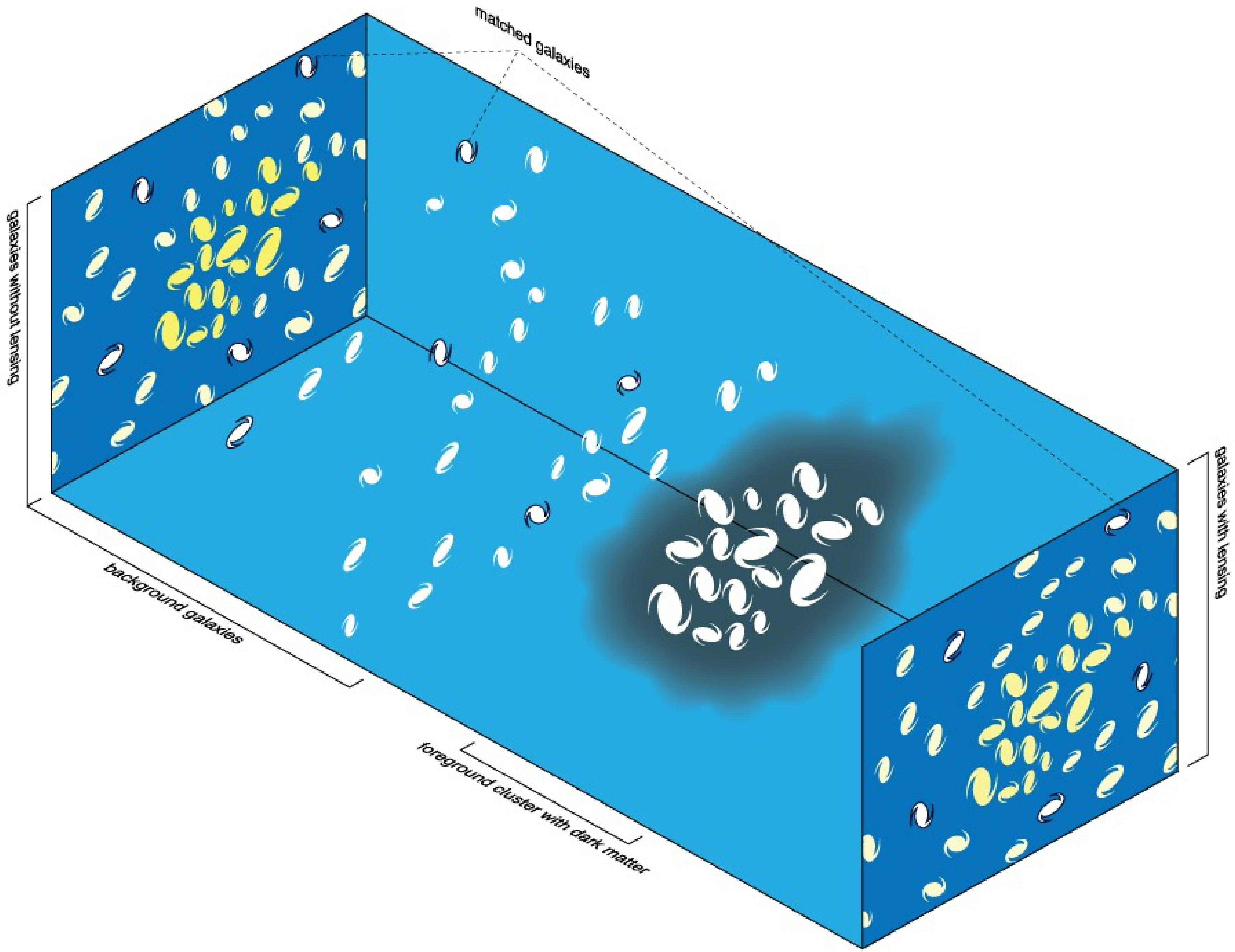
N.Sehgal et. al., 2011

Measuring Cluster Masses is Difficult

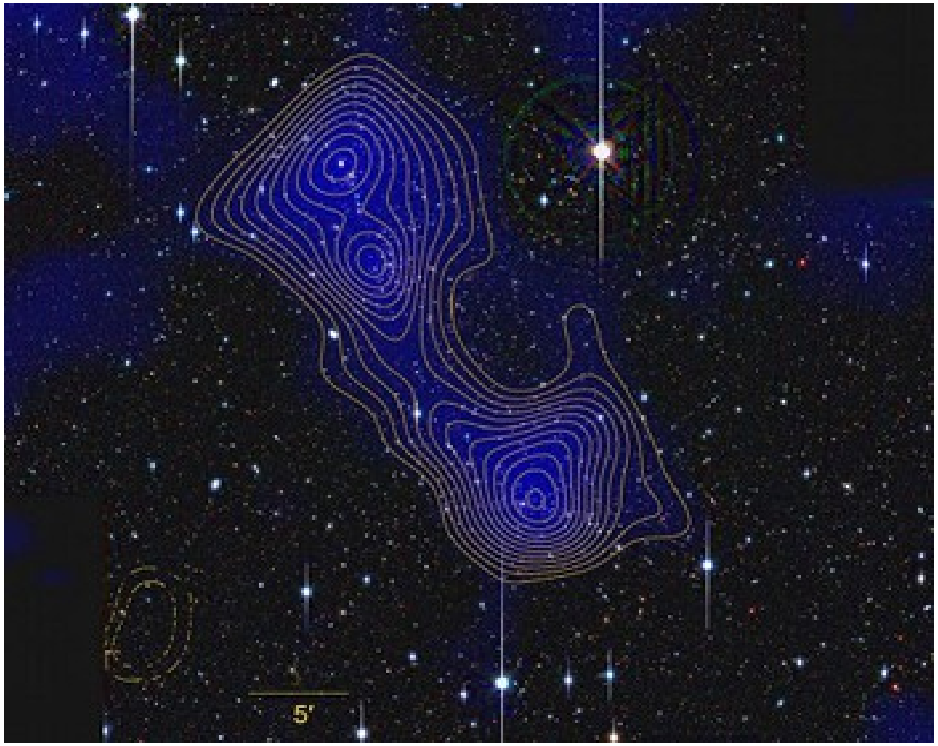


- Optical requires shaky assumptions about mass-to-light ratio
- X-ray -- gas temperature related to total mass if in hydrostatic equilibrium
  - Not necessarily in hydro equilibrium
  - Calibration uncertainties between different groups
  - 30-40% mass sensitivity
- Gravitational Lensing holds enormous promise for mass calibration

Optical Weak Lensing

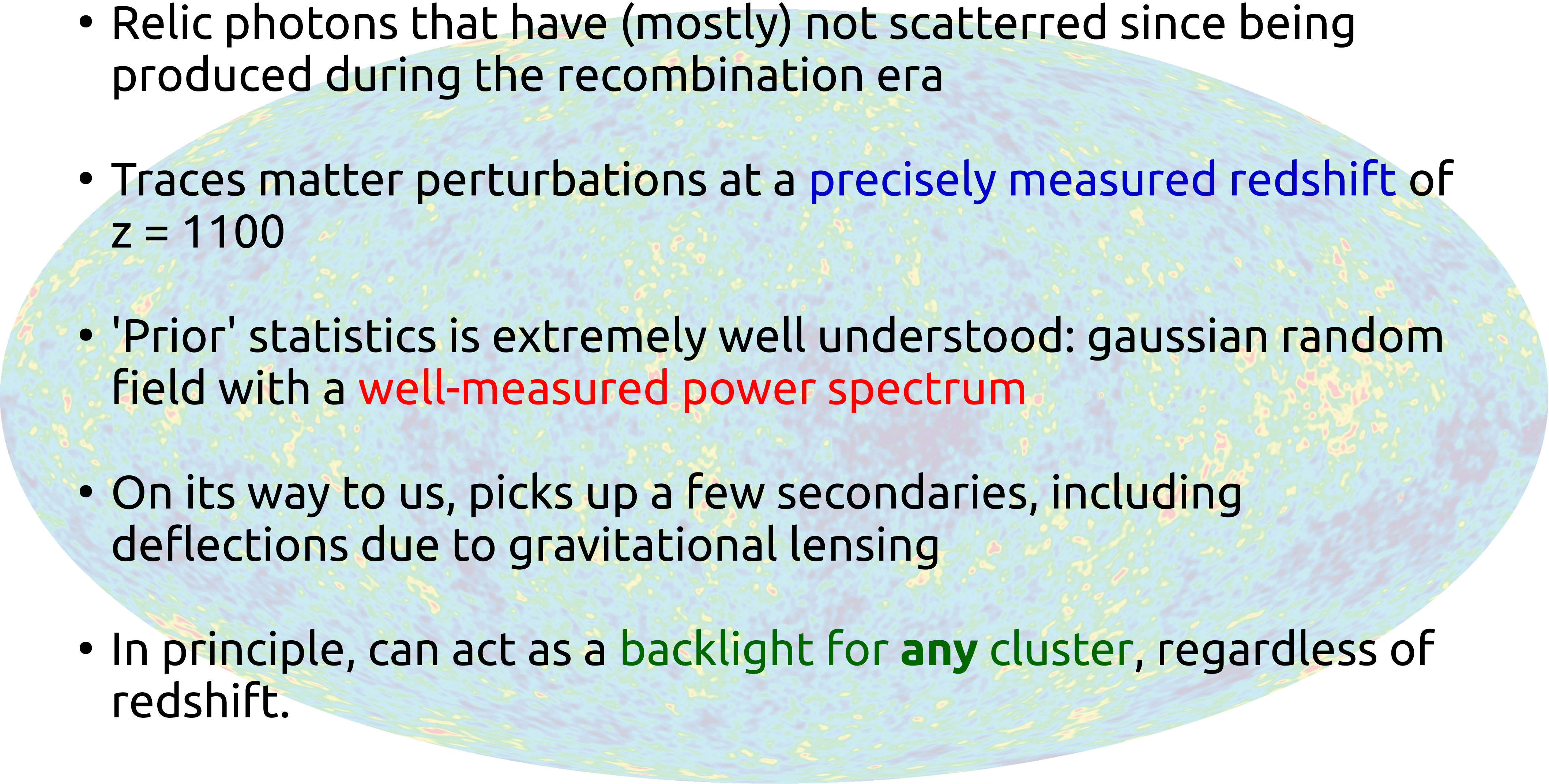


Optical Weak Lensing



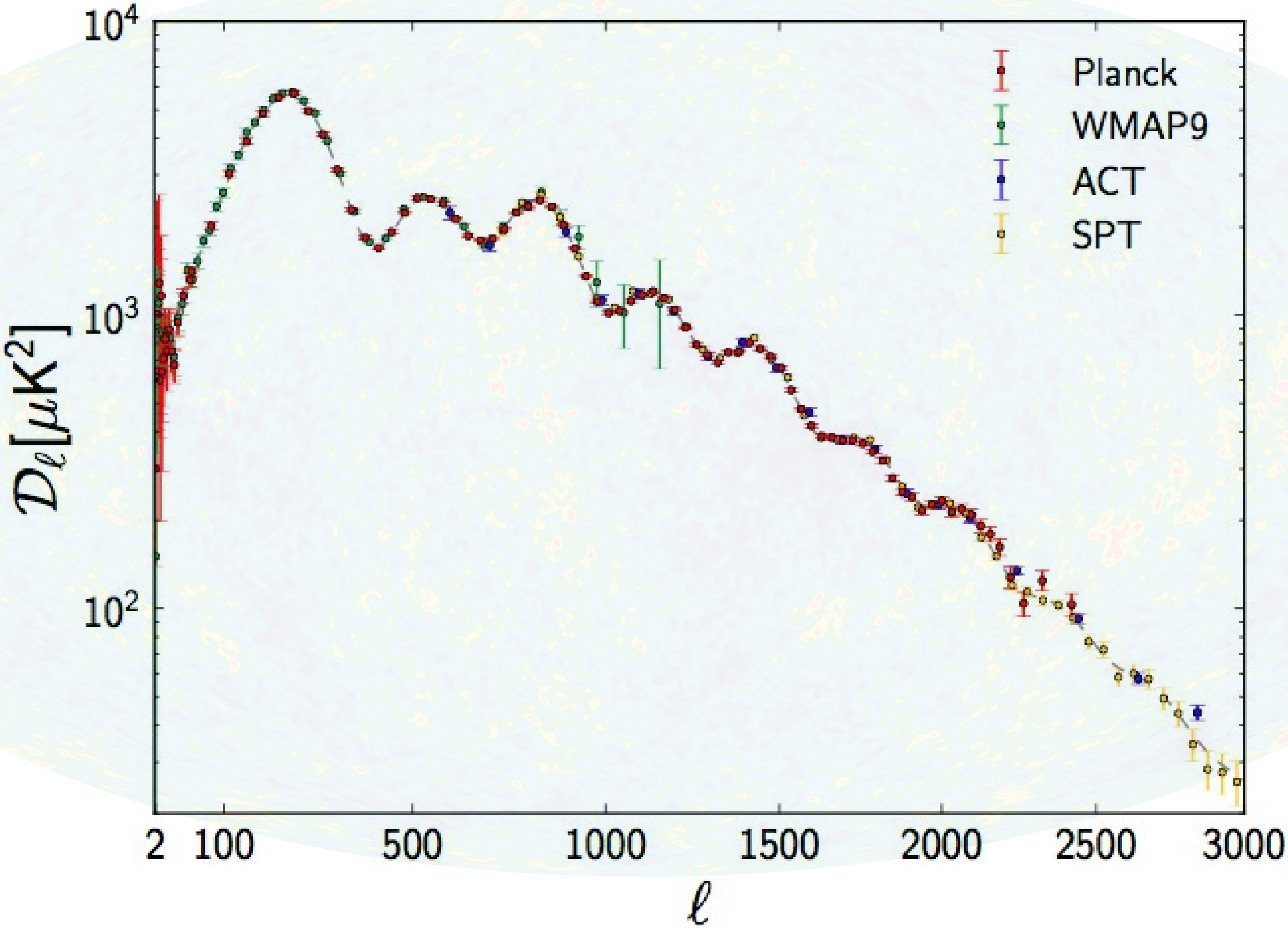
- Uncertainties from source galaxy redshift
- Uncertainties in 'prior' statistics, i.e., distribution of galaxy ellipticities (intrinsic alignments)
- Not many background galaxies at higher redshifts
- Modeling galaxies is incredibly difficult -- leads to multiplicative and additive biases

The Cosmic Microwave Background



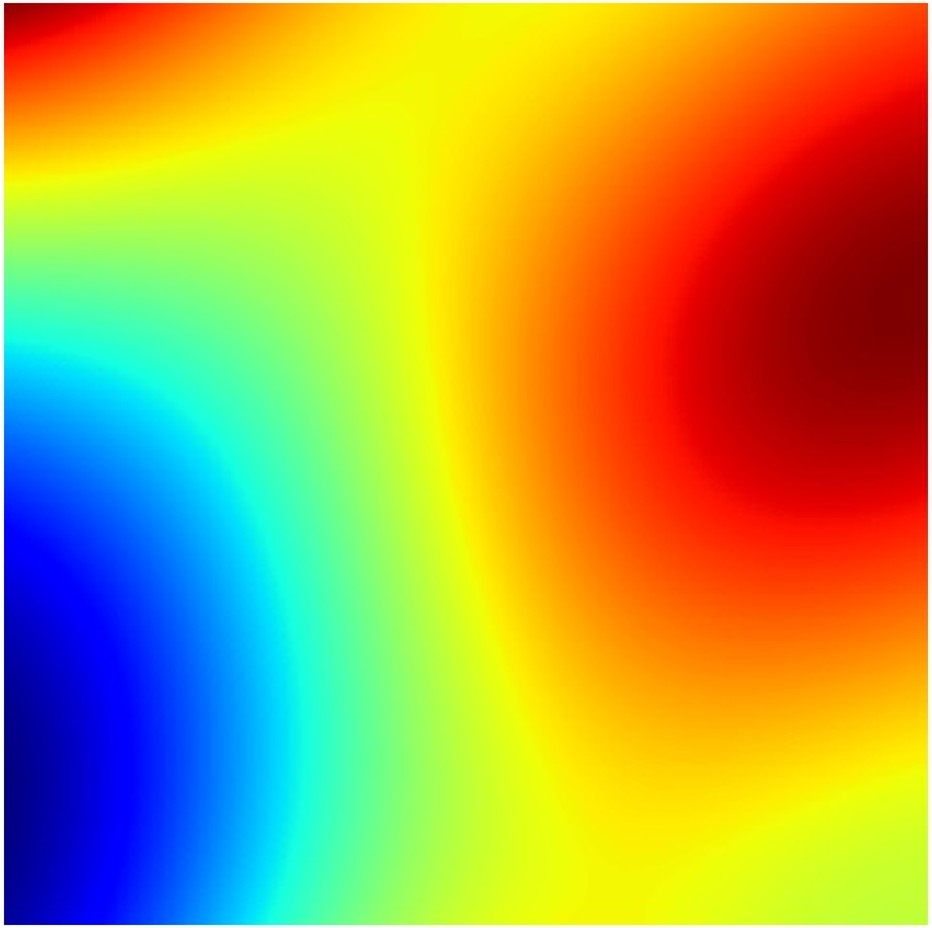
- Relic photons that have (mostly) not scatterred since being produced during the recombination era
- Traces matter perturbations at a precisely measured redshift of $z = 1100$
- 'Prior' statistics is extremely well understood: gaussian random field with a well-measured power spectrum
- On its way to us, picks up a few secondaries, including deflections due to gravitational lensing
- In principle, can act as a backlight for **any** cluster, regardless of redshift.

The CMB has low power on small scales



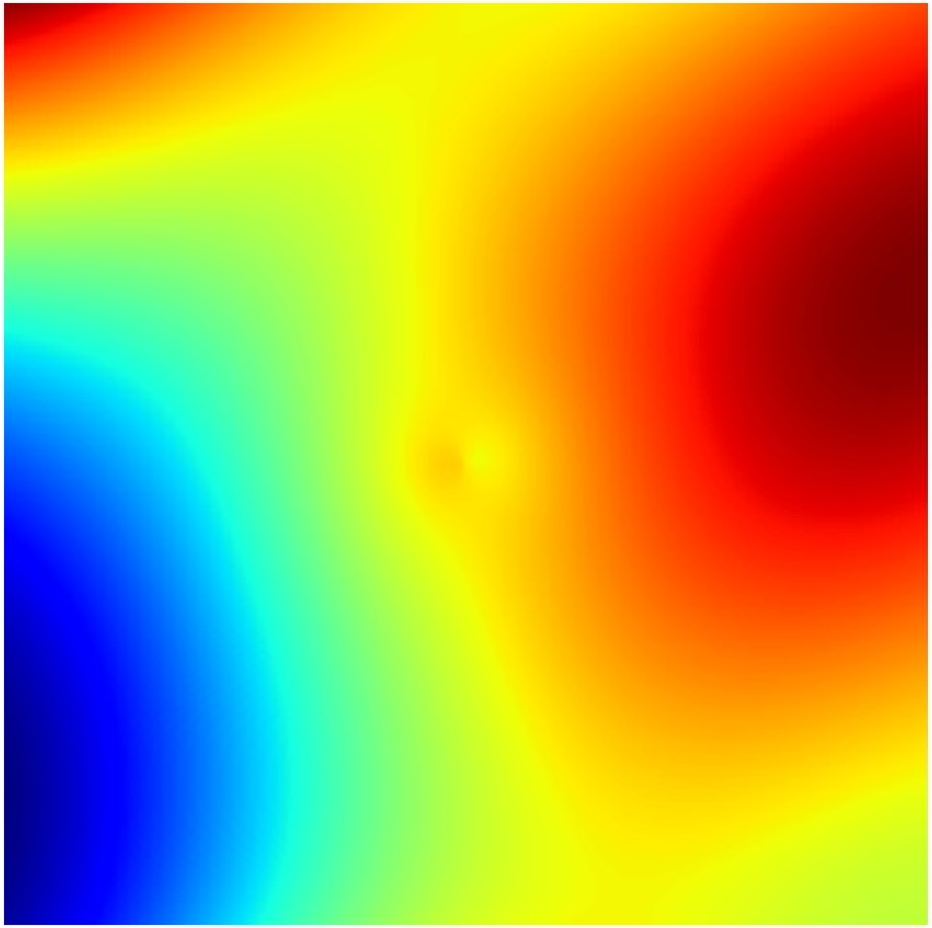
Lensing of the CMB

- Noiseless unlensed CMB
- 20' x 20' patch
- Mostly gradient



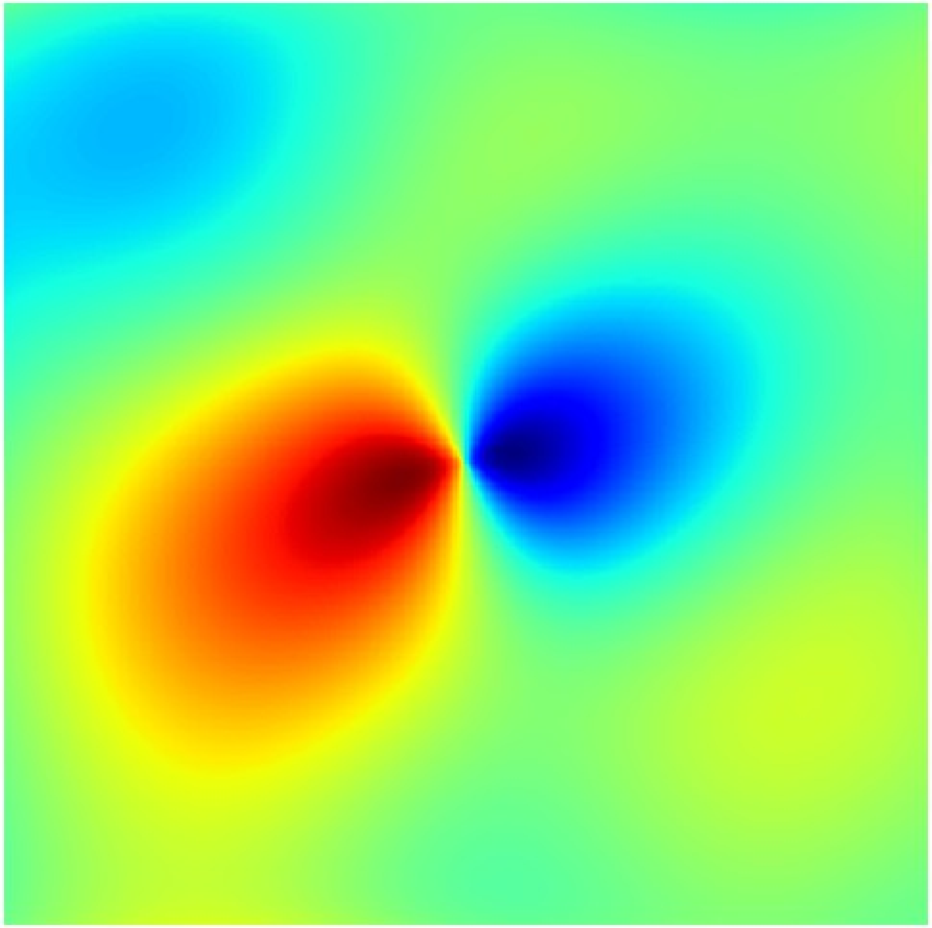
Lensing of the CMB

- Noiseless lensed CMB
- 20' x 20' patch
- Mostly gradient
- Lensed by M_{180}= $2x10^{15}$ M_{solar}



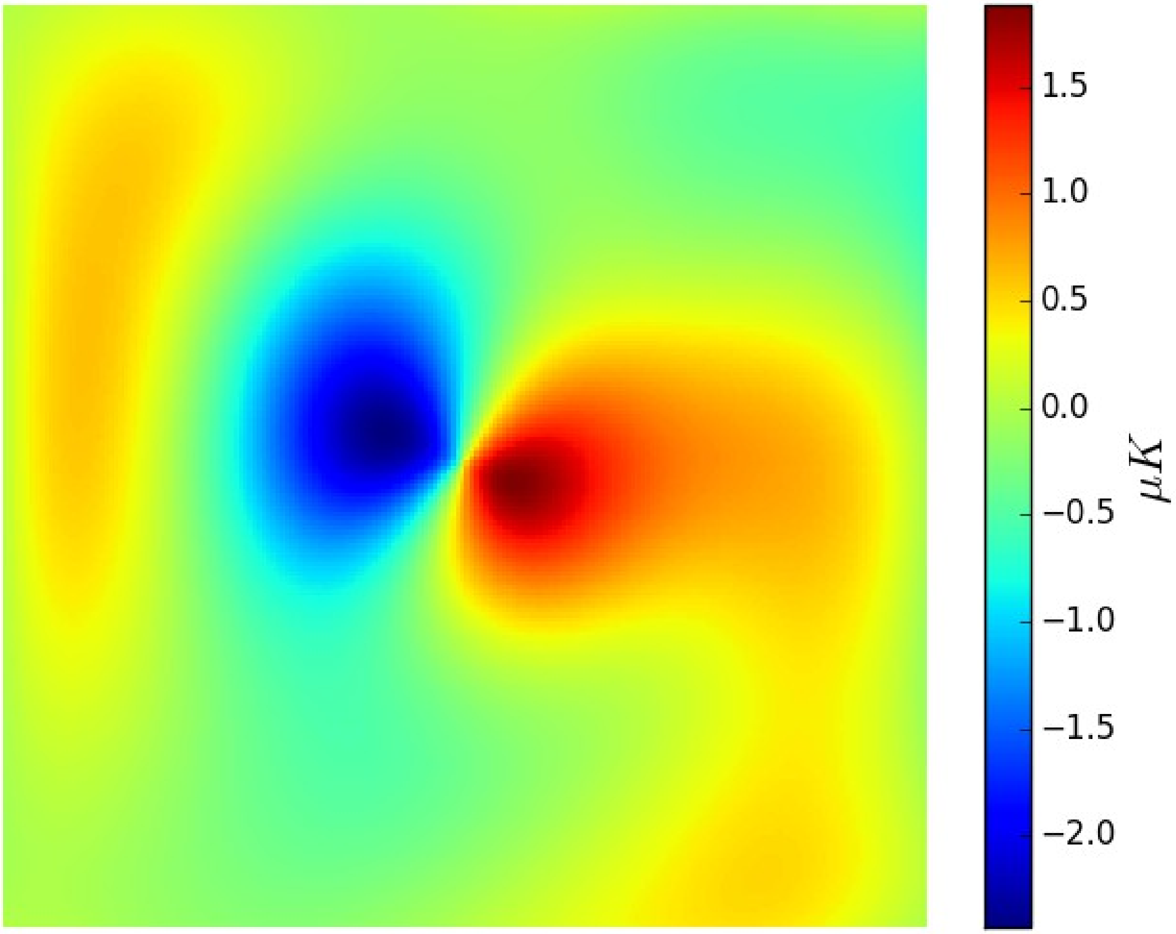
Lensing of the CMB

- Difference of lensed and unlensed CMB
- 20' x 20' patch
- Characteristic dipole along the direction of gradient



Lensing of the CMB

- Difference of lensed and unlensed CMB
- 20' x 20' patch
- Dipole signal is of the order of ~1-10μK

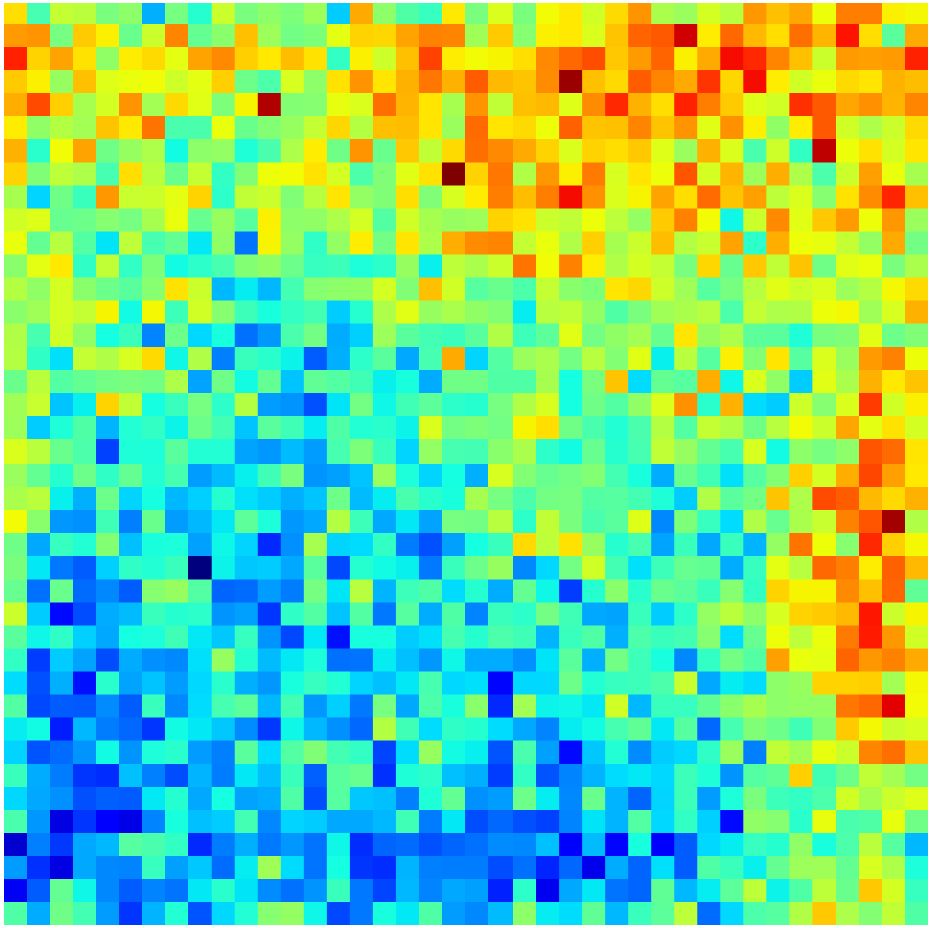


Lensing of the CMB

- Noisy lensed CMB

- 20' x 20' patch

- 1.4' beam
- 12μK-arcmin noise
- 0.5 arcmin pixel



Quadratic Estimators

A quadratic combination of the temperature field and its gradient provides an unbiased estimate of the lensing field

In the case of small-scale lensing by clusters, useful to see how this operates in real space

Some quick definitions

Lensing probes projected mass density

$$\Sigma(\hat{n}) = \int dr\, \rho(\hat{n}, r)$$

'Convergence' is the normalized projected mass density

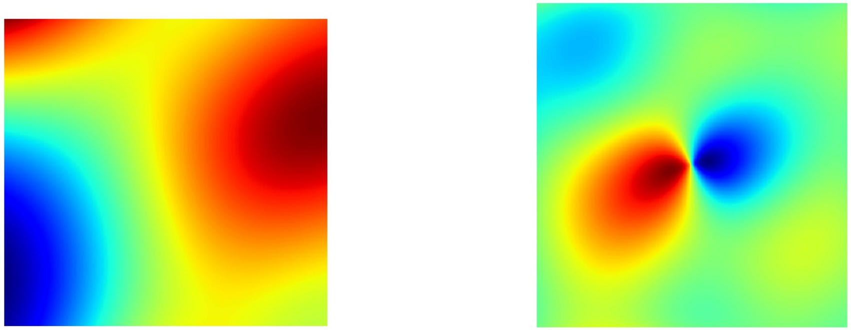
$$\kappa(\hat{n}) = \frac{\Sigma(\hat{n})}{\Sigma_{\mathrm{cr}}}$$

$$\Sigma_{\mathrm{cr}} = c^2 D_s / \left(4\pi G D_{ds} D_d\right)$$

Quadratic Estimator

Large-scale gradient Small-scale dipole

$$\hat{\kappa} \propto \vec{\nabla} \cdot \left[\left[\vec{\nabla} T \right]_{\mathrm{low}} \left[T(\vec{\theta}) \right]_{\mathrm{high}} \right]$$



Hu, DeDeo, Vale 2007

Quadratic Estimator

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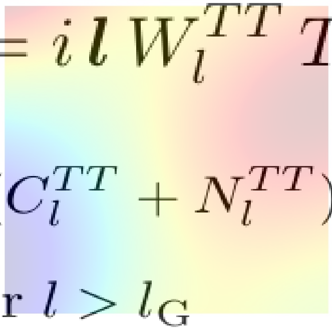
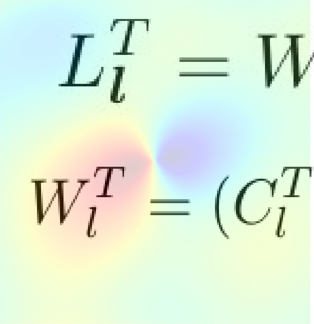


$$\mathbf{G}_{\boldsymbol{l}}^{TT} = i\,\boldsymbol{l}\,W_l^{TT}\,T_{\boldsymbol{l}},$$

$$W_l^{TT} = \tilde{C}_l^{TT}(C_l^{TT} + N_l^{TT})^{-1}$$

$$W_l^{TT} = 0 \text{ for } l > l_{\mathrm{G}}$$



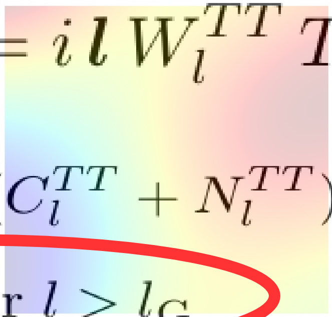
$$L_{\boldsymbol{l}}^{T} = W_l^{T}\,T_{\boldsymbol{l}},$$

$$W_l^{T} = (C_l^{TT} + N_l^{TT})^{-1}.$$

Hu, DeDeo, Vale 2007

Quadratic Estimator

Note: Slight tweak from Hu, Okamoto (2001) used for LSS lensing, which develops bias for κ~O(1). Practically removes bias for ~10^{14} M_{solar} clusters.



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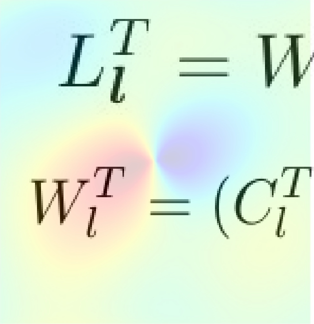

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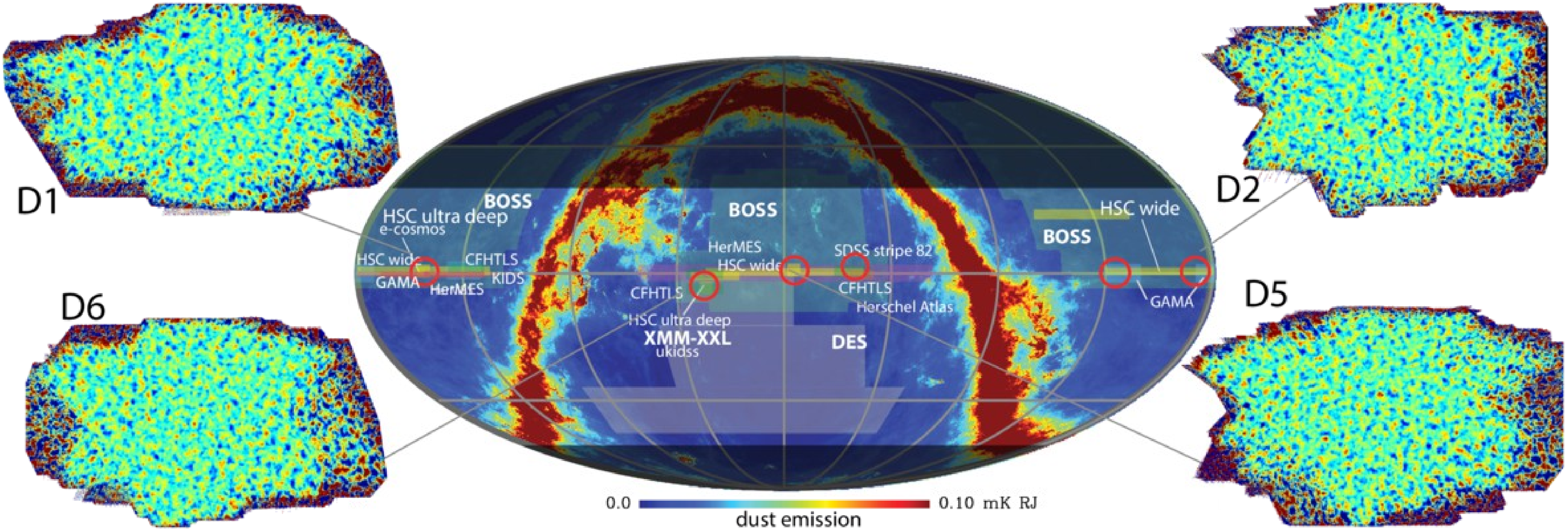
Hu, DeDeo, Vale 2007

The Atacama Cosmology Telescope

ACTPol's polarization-sensitive detector deployed in 2013

- 1.3 arcmin resolution
- 146 GHz
- Season 1 (2013) 'deep' scans at 12μK-arcmin sensitivity

The Atacama Cosmology Telescope



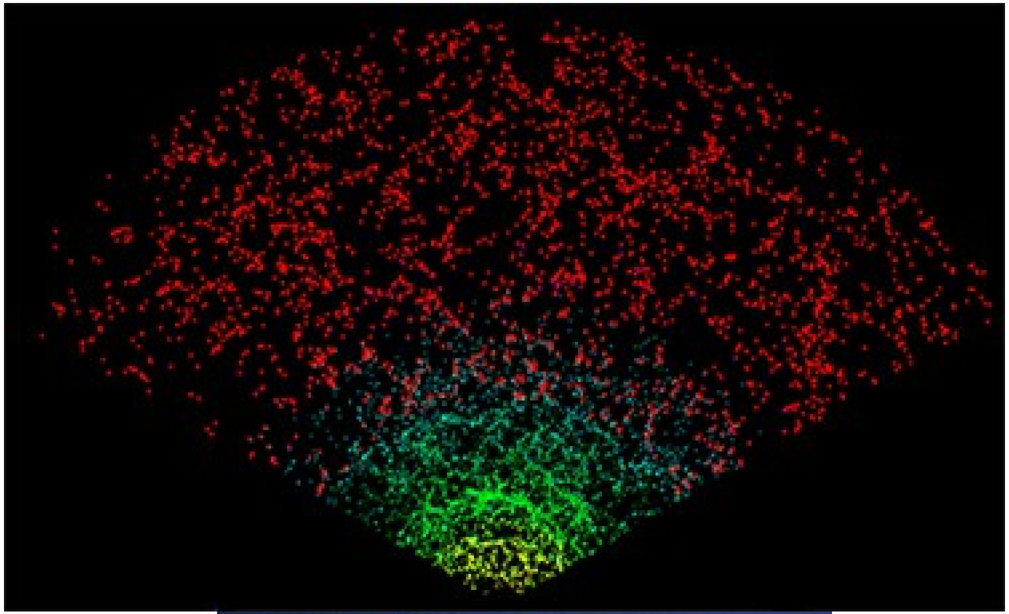
Three night-time-only observing regions Deep 1, 5, and 6 that overlap with the BOSS survey

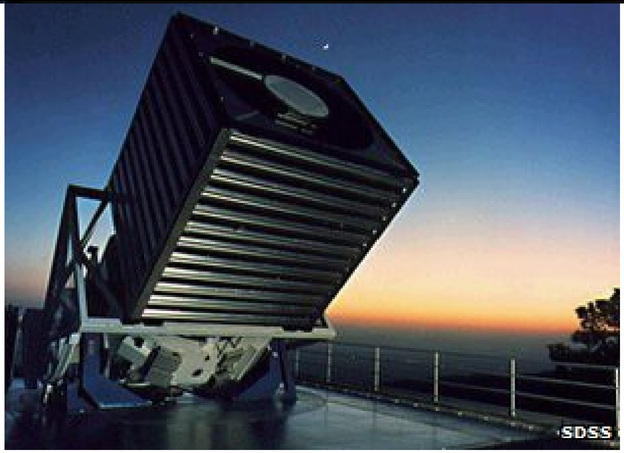
SDSS/BOSS
CMASS galaxies as tracers of Halos

- High-z (0.4<z<0.7) luminous galaxies selected similar to LRGs

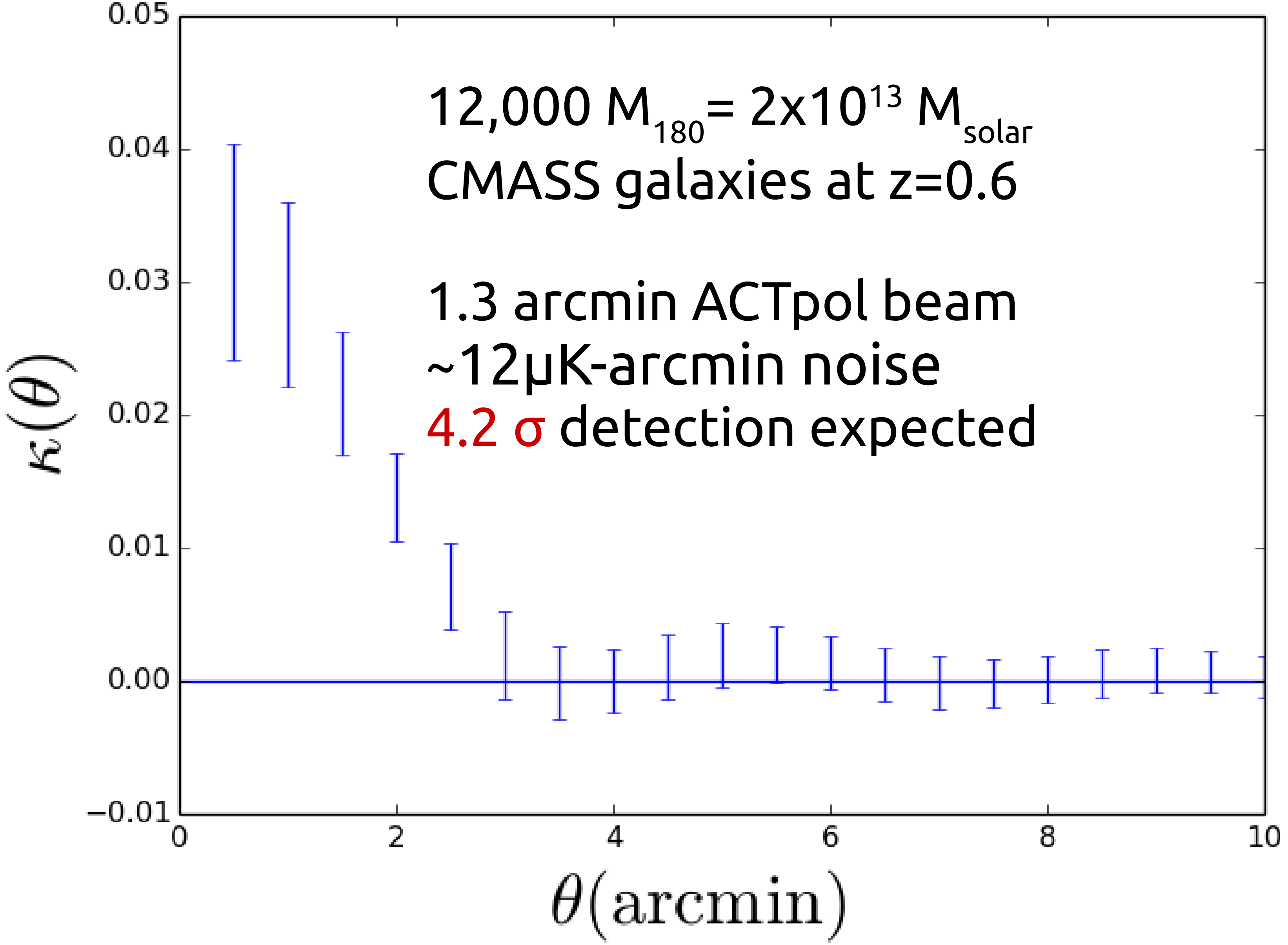
- Volume-limited, sufficient sample to probe large scale structure

- Reside in ~10^{13} M_{solar} mass halos, mostly at the center
  (Miyatake et. al. 2013)





Expected signal from simulations

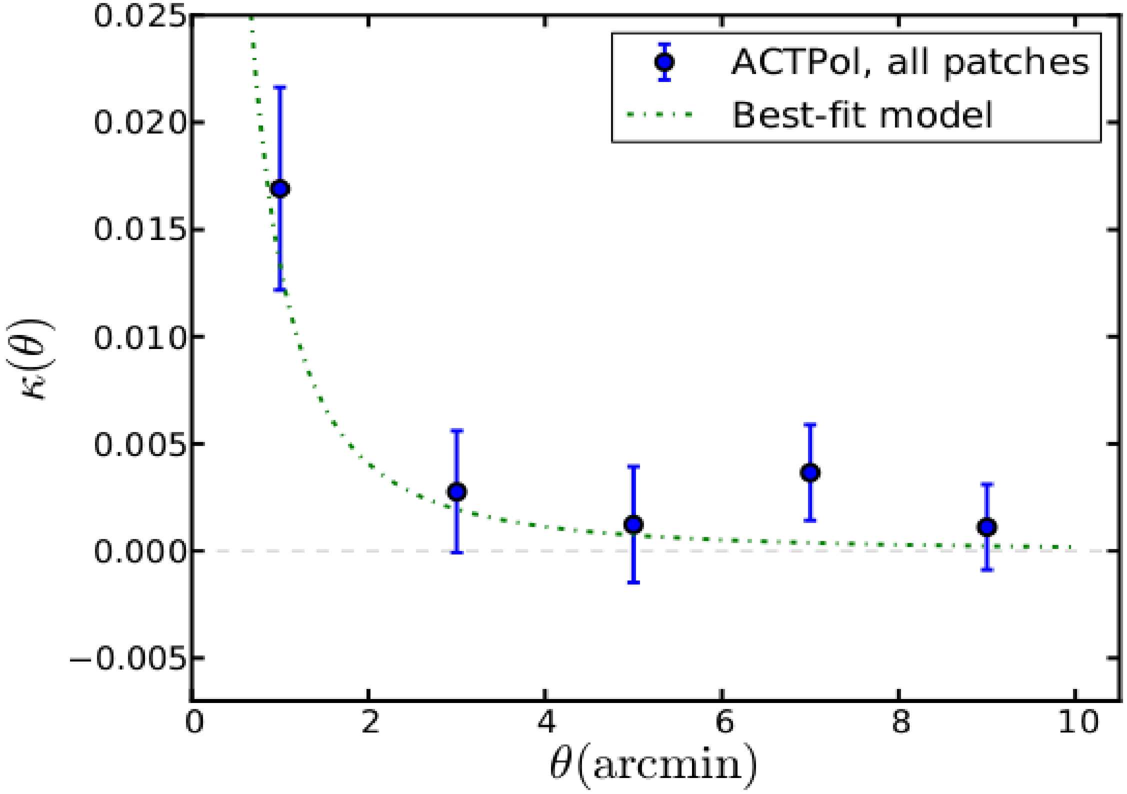


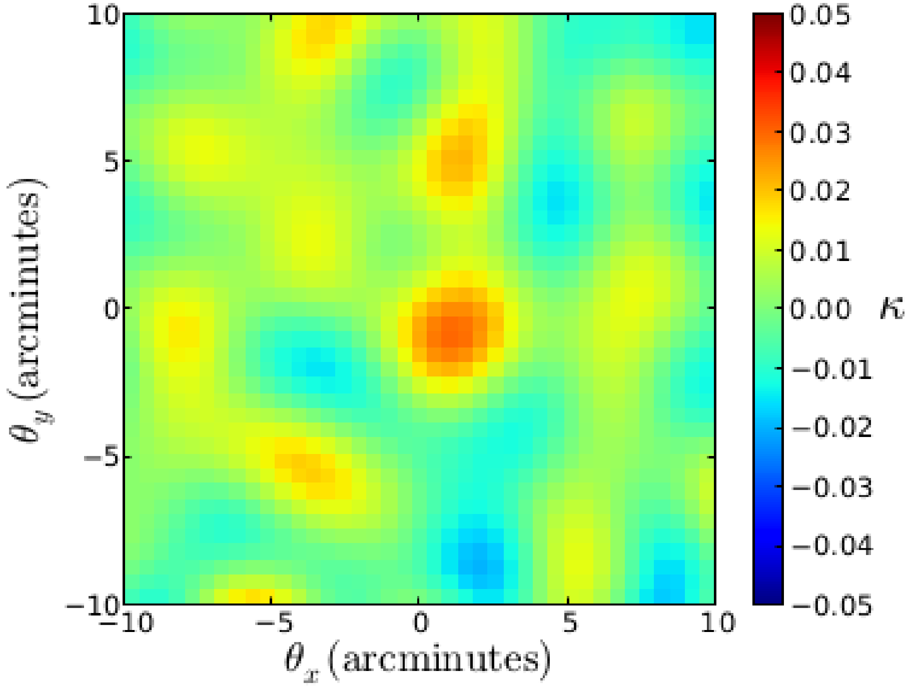
12,000 M_{180}= $2x10^{13}$ M_{solar}
CMASS galaxies at z=0.6

1.3 arcmin ACTpol beam
~12μK-arcmin noise
4.2 σ detection expected

Results: Detection

MM, N.Sehgal et. al., **Phys. Rev. Lett. 114, 151302**



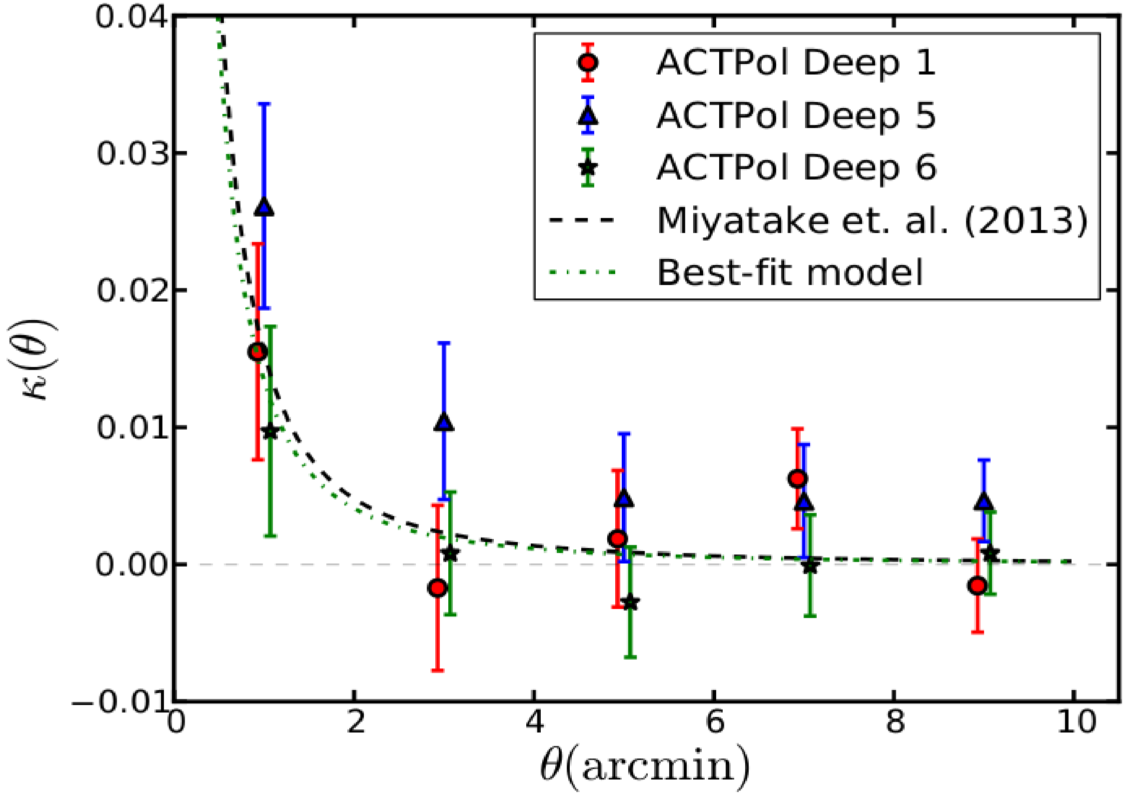


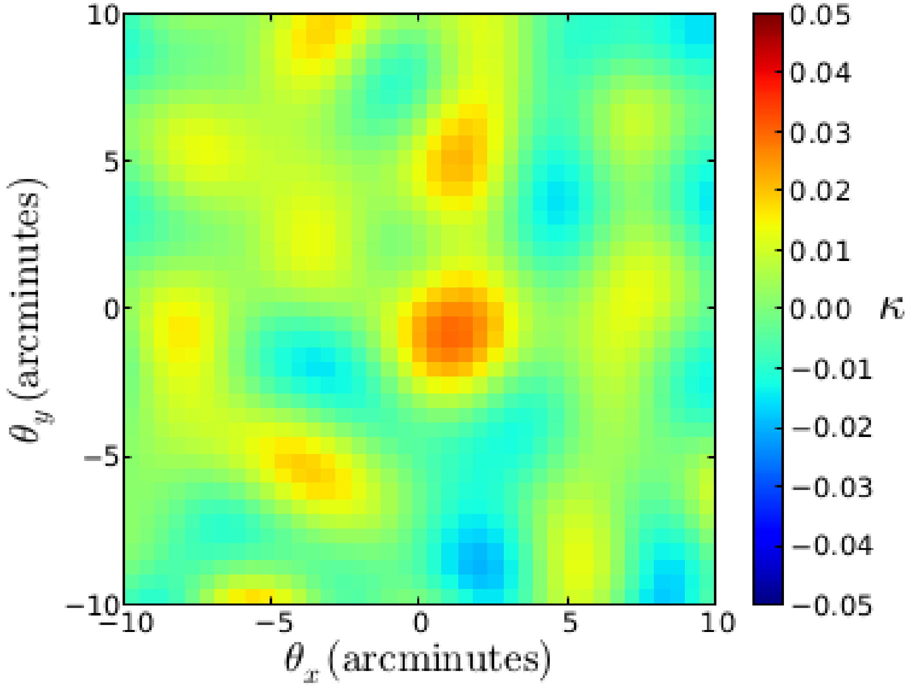
We detect halo lensing from 12,000 stacked CMASS galaxies at S/N of 3.2 sigma

Best-fit of M_{200} = 2.0+-0.7 10^{13} M_{solar} and C_{200} = 5.4+-0.8

Results:
Excess in each patch

MM, N.Sehgal et. al., **Phys. Rev. Lett. 114, 151302**

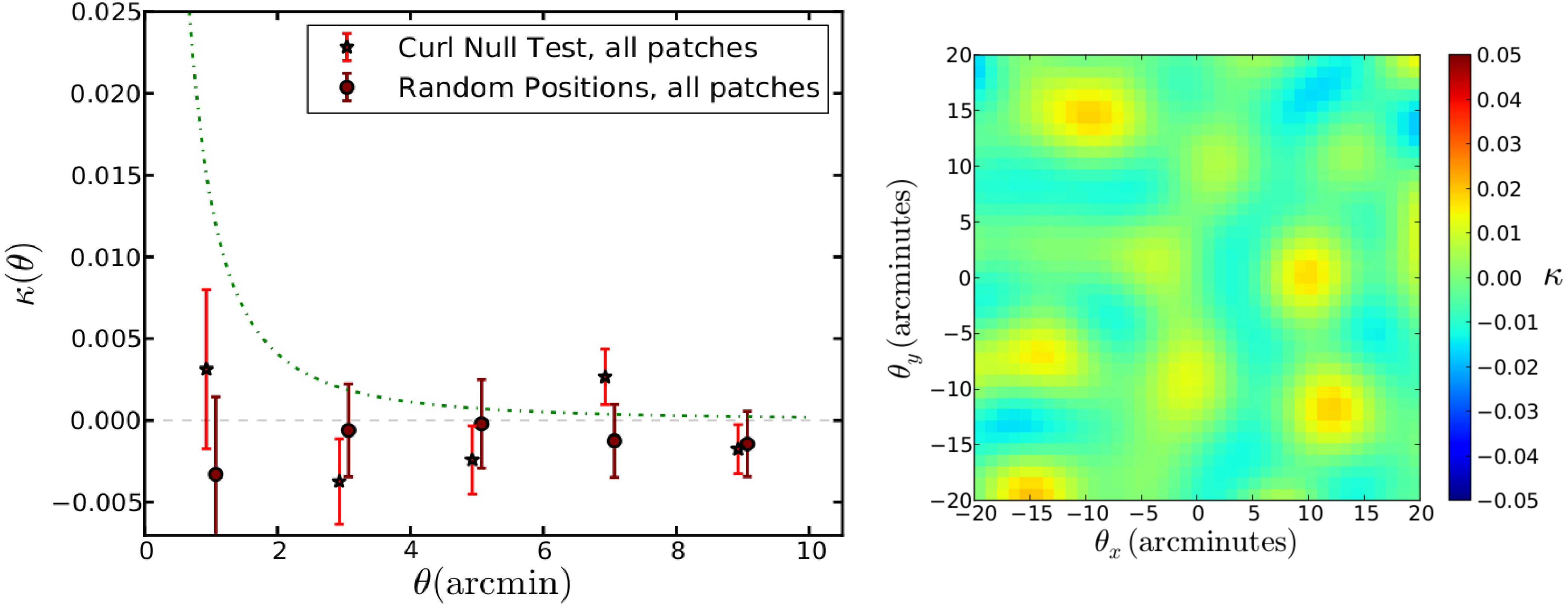




Excess seen in all three observing regions.
Signal consistent with Optical Weak Lensing measurement from Miyatake et. al. 2013.

Results:
Null Tests (Random)

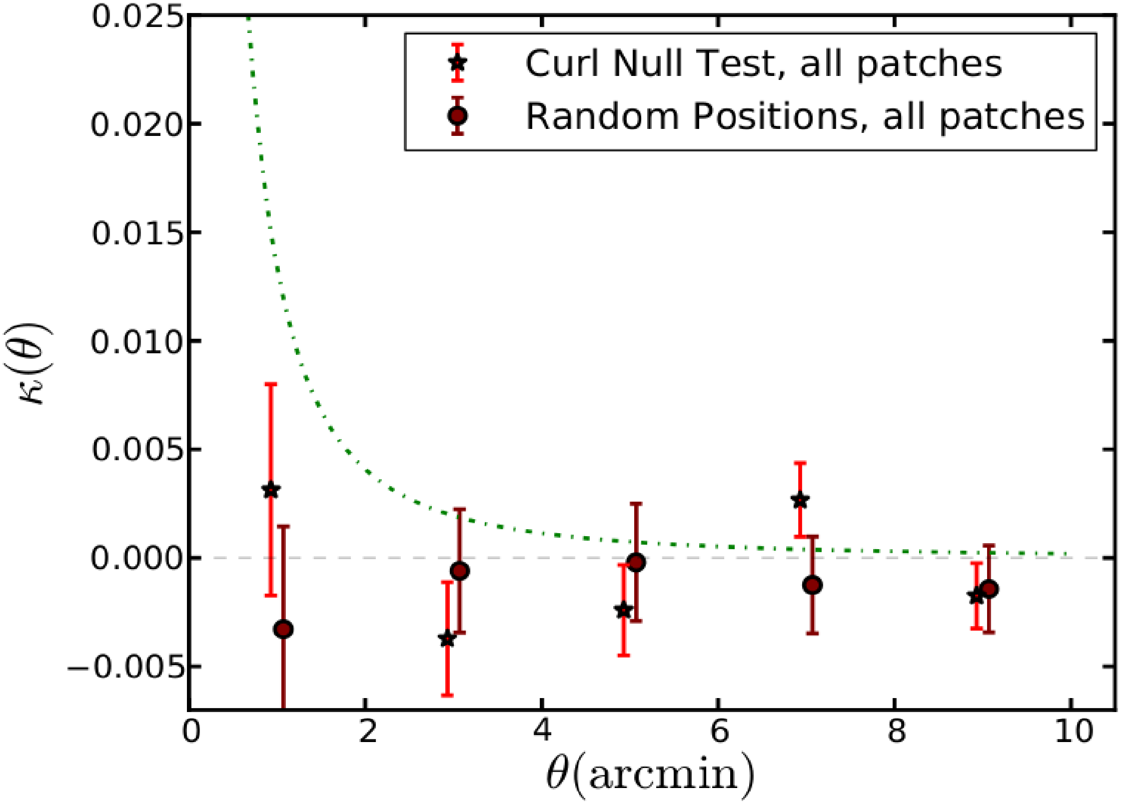
MM, N.Sehgal et. al., **Phys. Rev. Lett. 114, 151302**

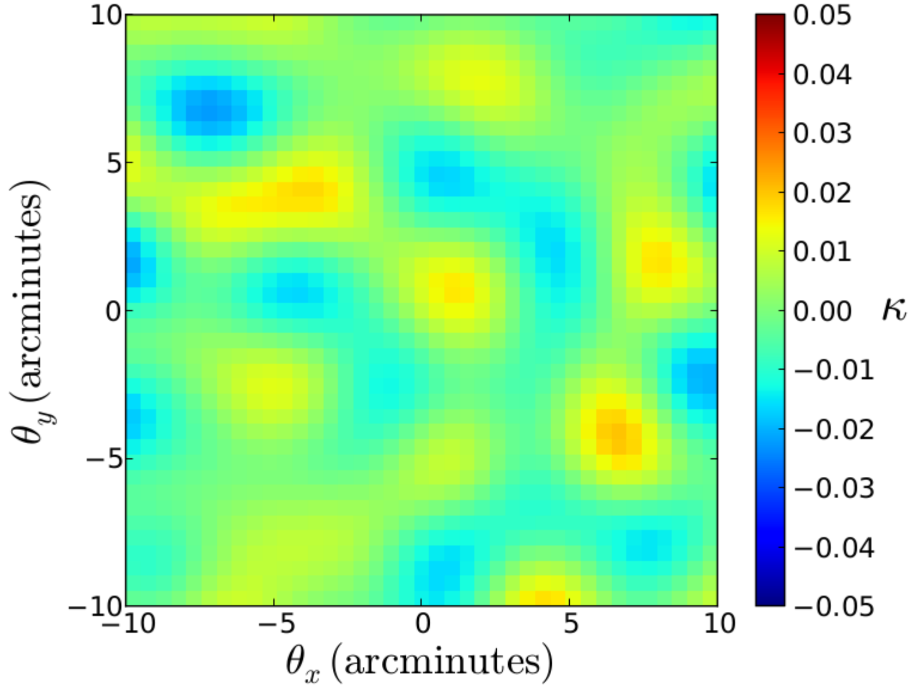


RANDOM LOCATIONS

Results:
Null Tests (Curl)

MM, N.Sehgal et. al., **Phys. Rev. Lett. 114, 151302**

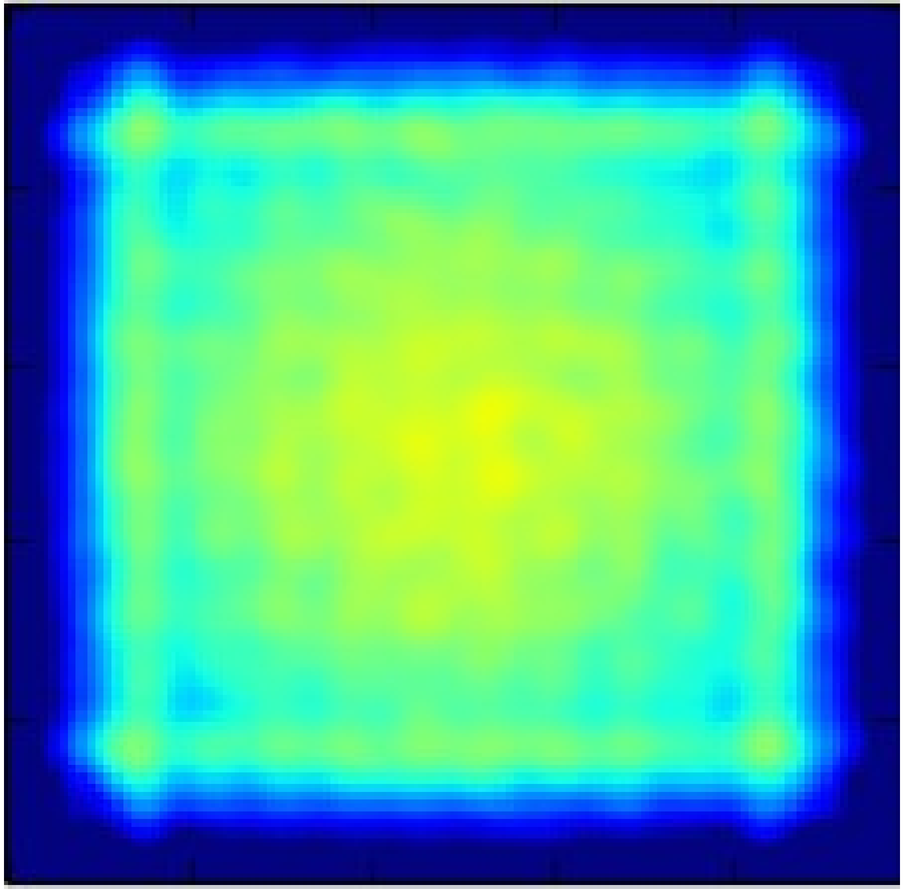




CURL INSTEAD OF DIV

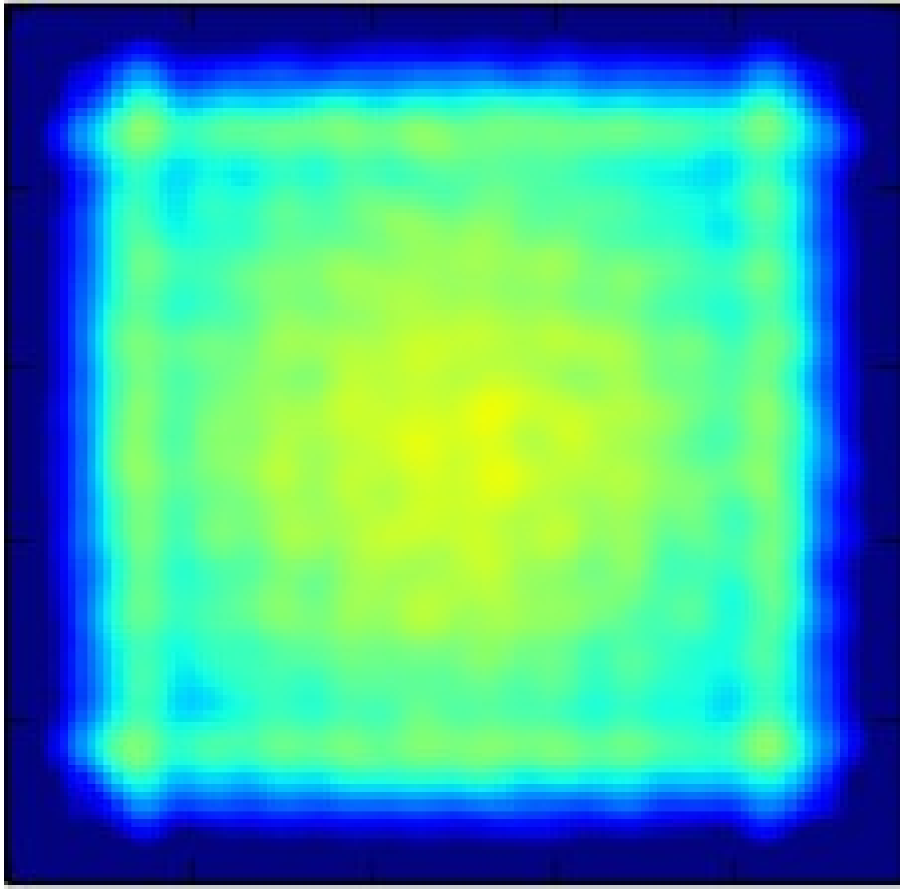
Analysis: mean-field subtraction

Application of an apodization mask (taper) induces 'mean-field'. Necessary to subtract this out.



Analysis: mean-field subtraction

Can be thought of as the effective convergence field due to a taper



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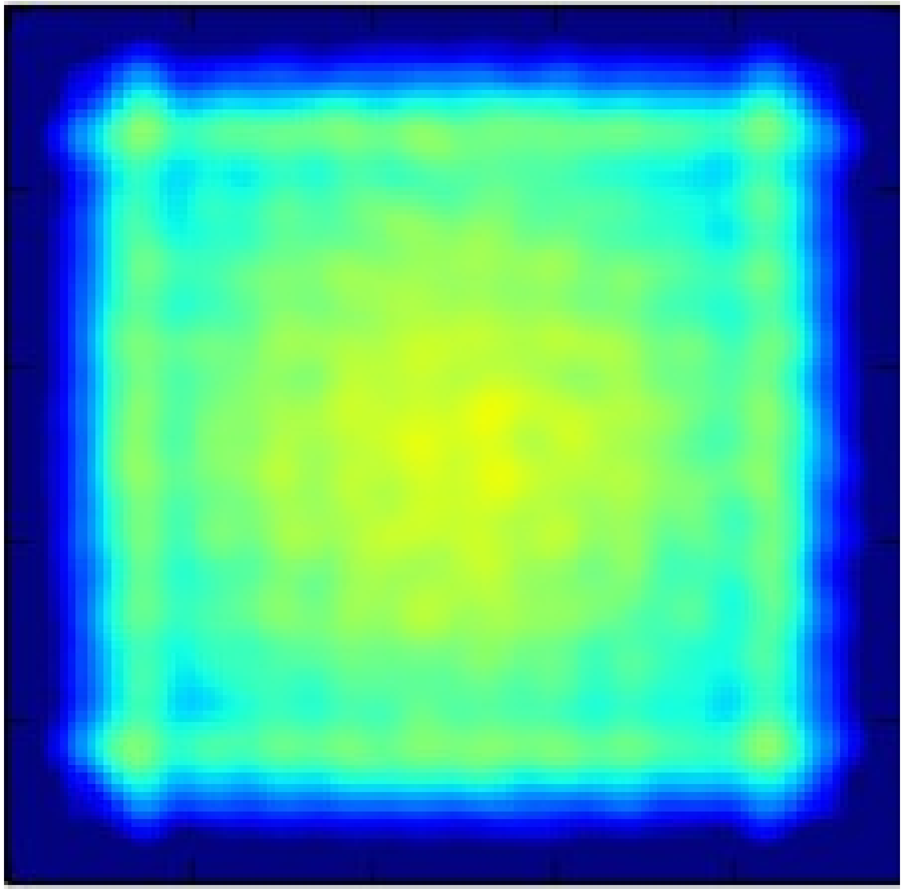


- Sensitive to small-scale power; difficult to calibrate out using simulations
- Mean-field estimated by large stack on random positions
- Any excess seen in stack is excess above random locations

Analysis: covariance matrix

- Covariance matrix calculated from 50 independent simulations
    - Stack of CMASS locations on simulated CMB maps
    - Each simulation is identical to pipeline for each patch and uses noise power estimated from data splits
    - Captures covariance induced by overlap of stacked stamps and clustering of CMASS galaxies

Analysis: thermal SZ bias

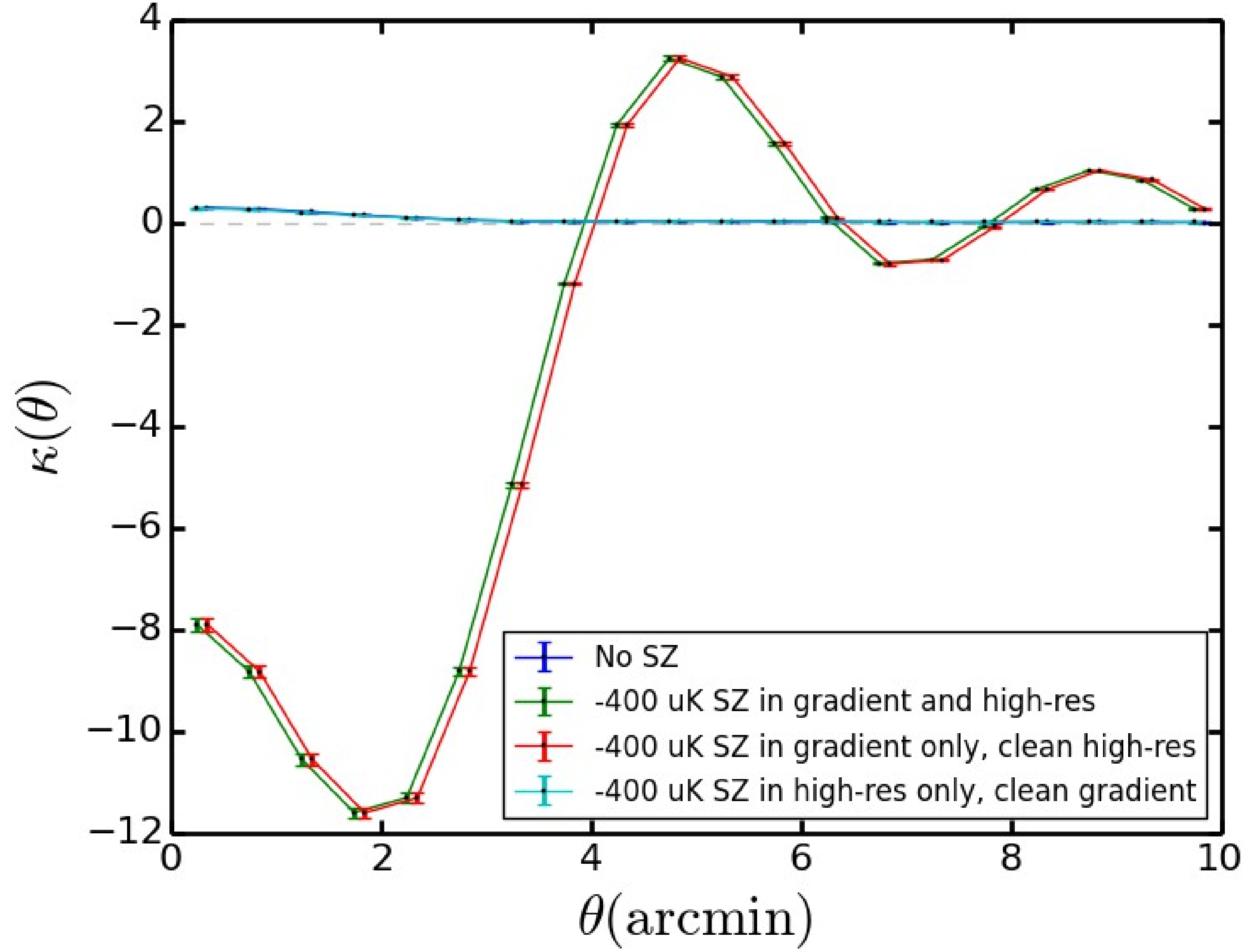
- CMASS halos have low tSZ contamination (<10uK) compared to massive clusters (~400uK)

- Effect of bias is mostly suppression of signal in first bin, but not expected to be more than 0.1 sigma for CMASS

- Bias scales roughly as $\sim\Delta T^2$ (because estimator is quadratic), so much more severe for massive halos

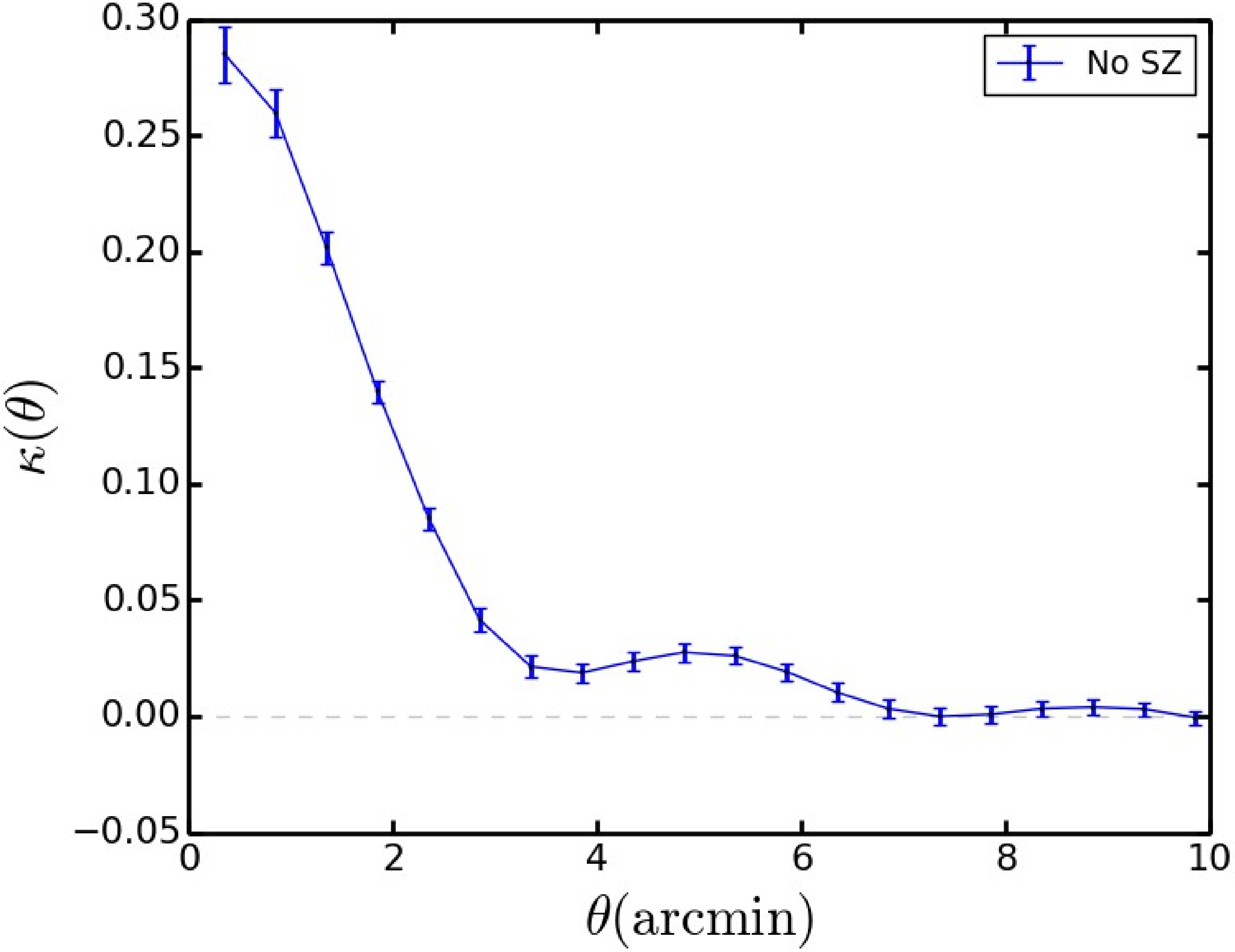
Analysis: thermal SZ bias

Serious problem for single-frequency observations of massive clusters



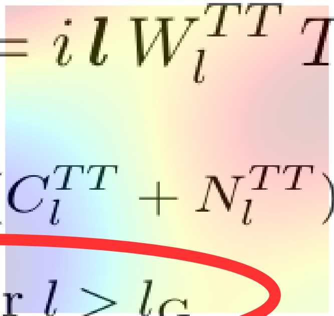
Analysis: thermal SZ bias

You could use component-separated maps and take a HUGE noise hit



Reminder: Quadratic Estimator

Gradient cut off at l=2000



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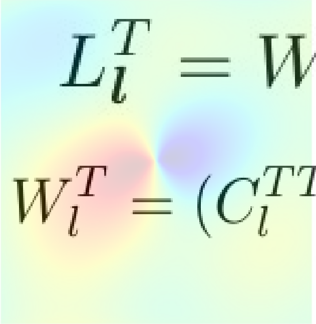
$$W_l^{TT} = 0 \text{ for } l > l_{\mathrm{G}}$$

Full-resolution map



$$L_{\boldsymbol{l}}^{T} = W_l^{T}\, T_{\boldsymbol{l}},$$

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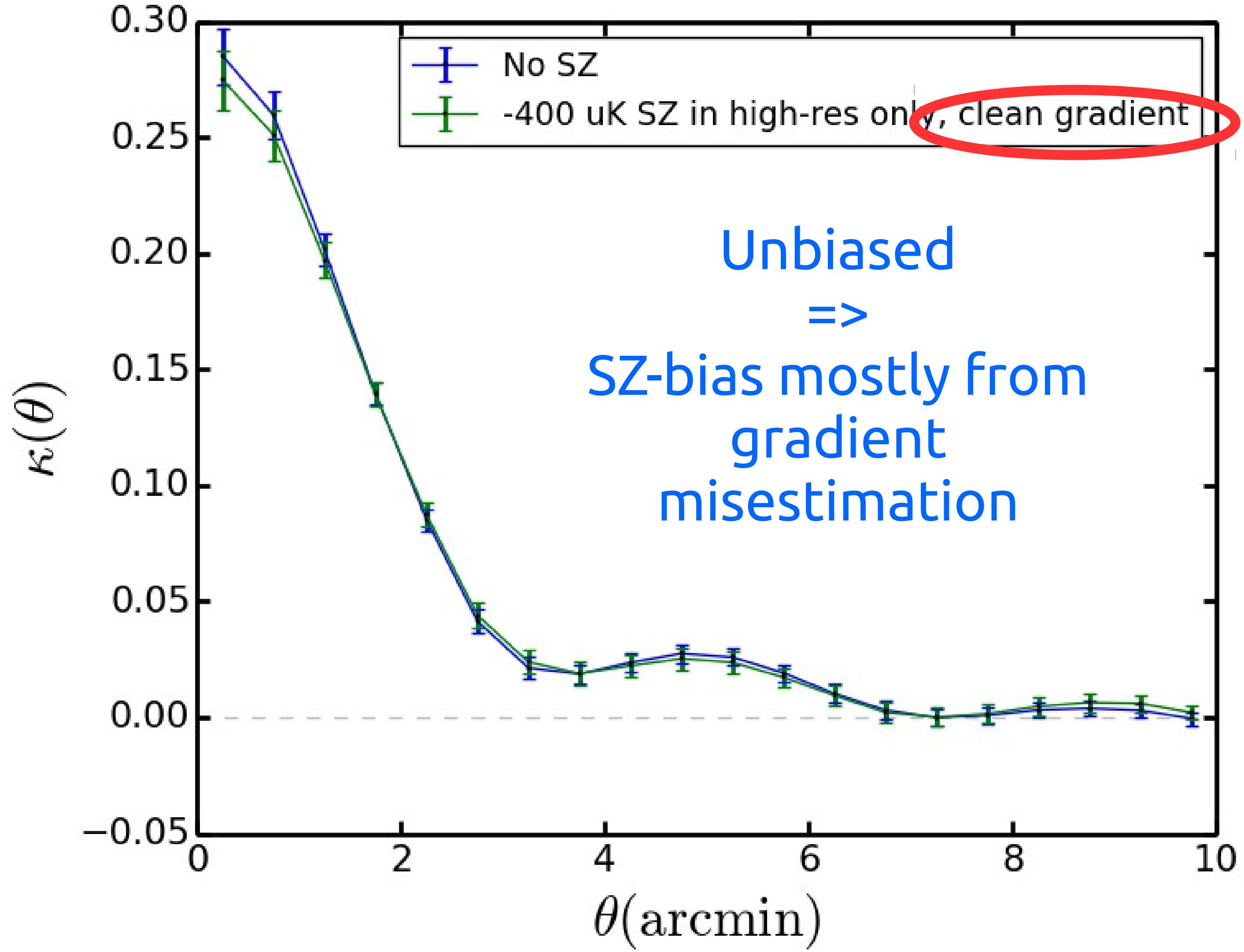
Analysis: thermal SZ bias

You could use component-separated maps and take a HUGE noise hit
OR
use Planck SZ-cleaned maps for gradient + (contaminated) high-res map



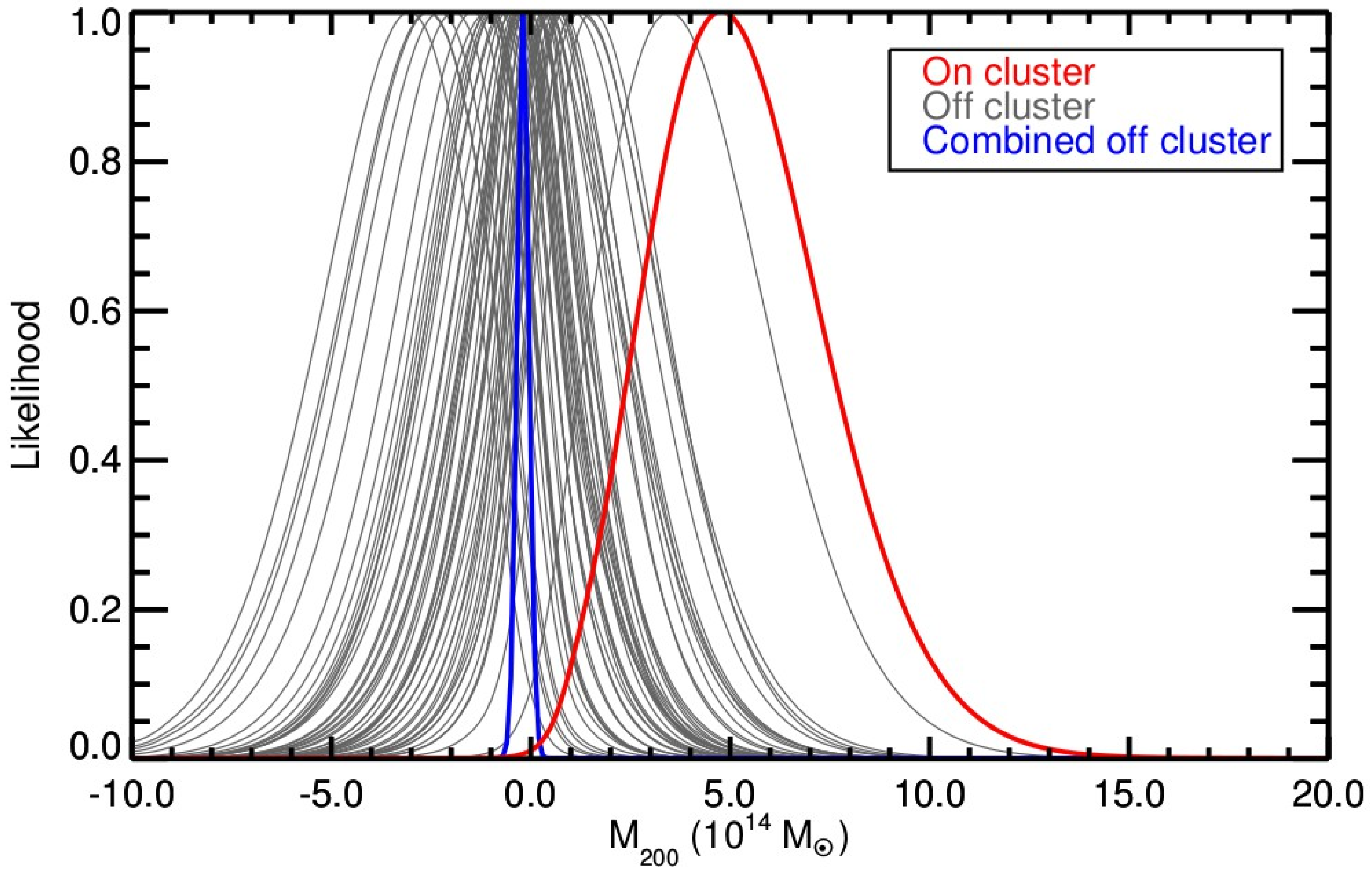
Unbiased
=>
SZ-bias mostly from gradient misestimation

SPTpol measurement

- Shortly followed ACTPol measurement (Baxter et. al.)
- 513 SZ selected clusters (~5×10^{14} M_{solar})
- ~ - 400 uK SZ severely biases pipeline
- Combined frequencies to remove SZ
- Went from 18 uK' noise to 55 uK' noise in cleaned maps
- Note: Not a quadratic estimator but a pixel-level likelihood approach

SPTpol measurement

3.0 sigma



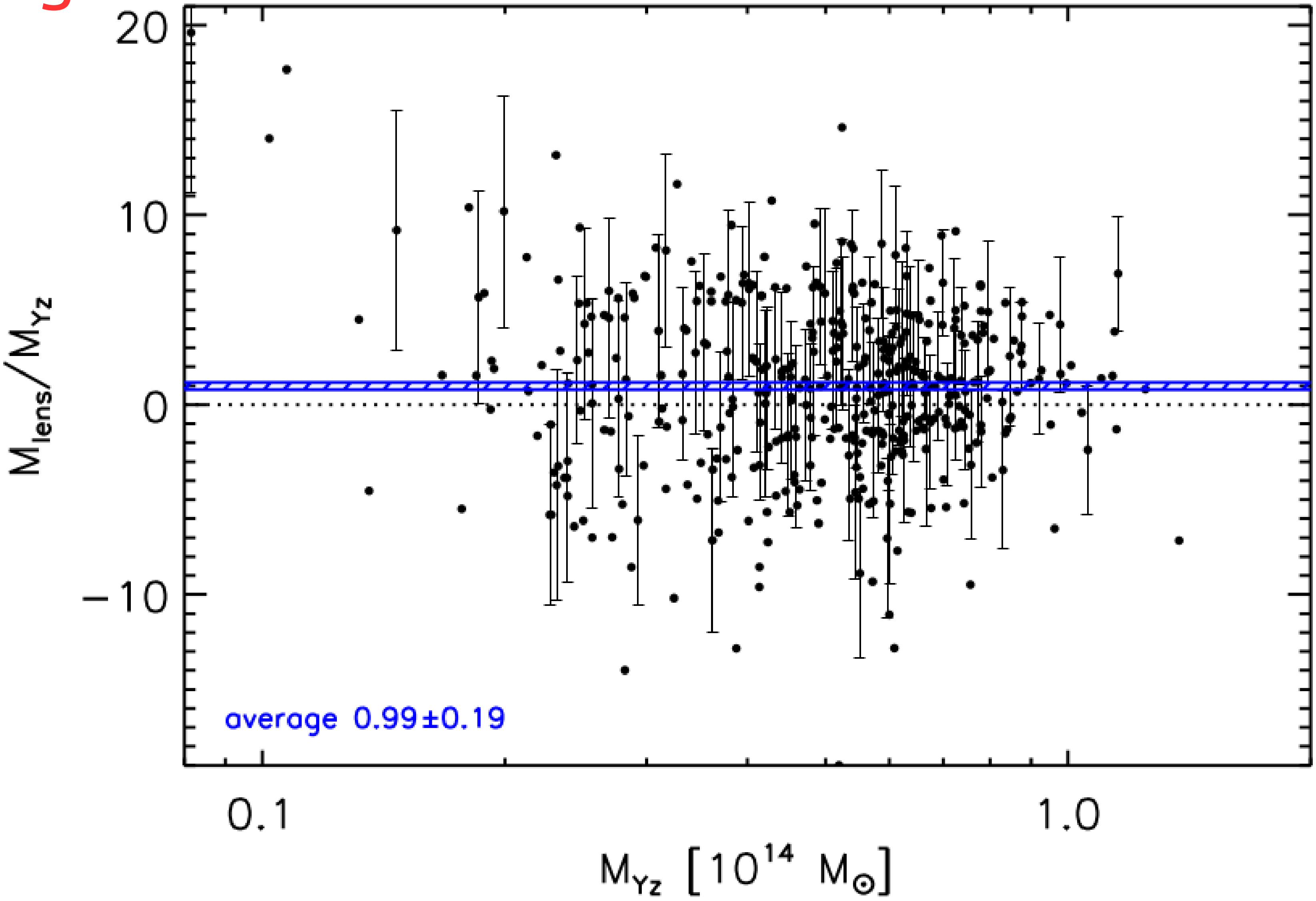
Baxter et. al. 2014 arXiv astro-ph:1412.7521

Planck measurement

- Matched filter applied to reconstruction from quadratic estimator (profile shape assumed)
- 439 SZ selected clusters
- Hydrostatic mass bias (1-b) between X-ray flux and true mass was the dominant uncertainty in 2013 analysis
- 2015 analysis constrains 1-b using weak lensing and CMB lensing measurements

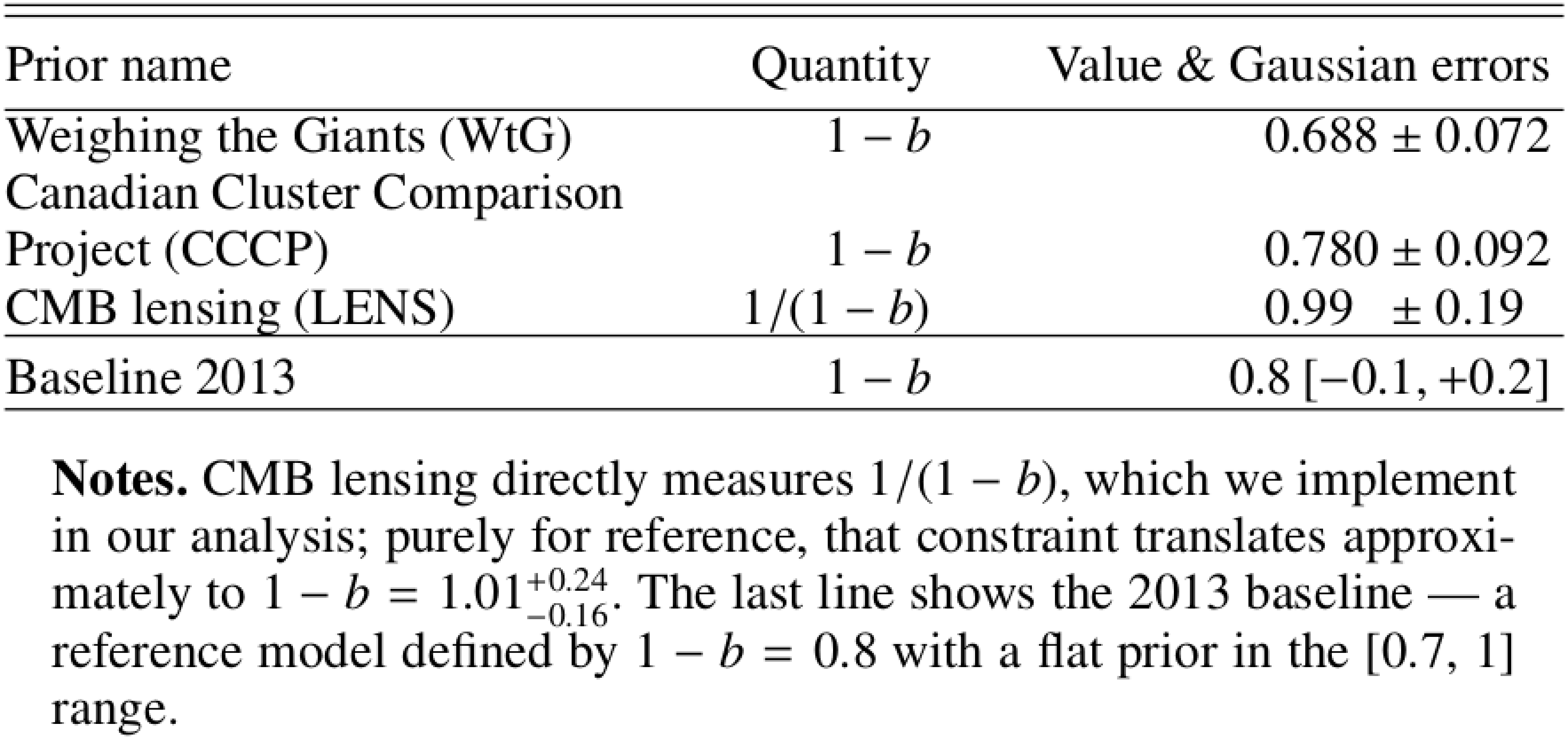
Planck measurement

~5 sigma



Planck 2015 XXIV

Planck: SZ calibration



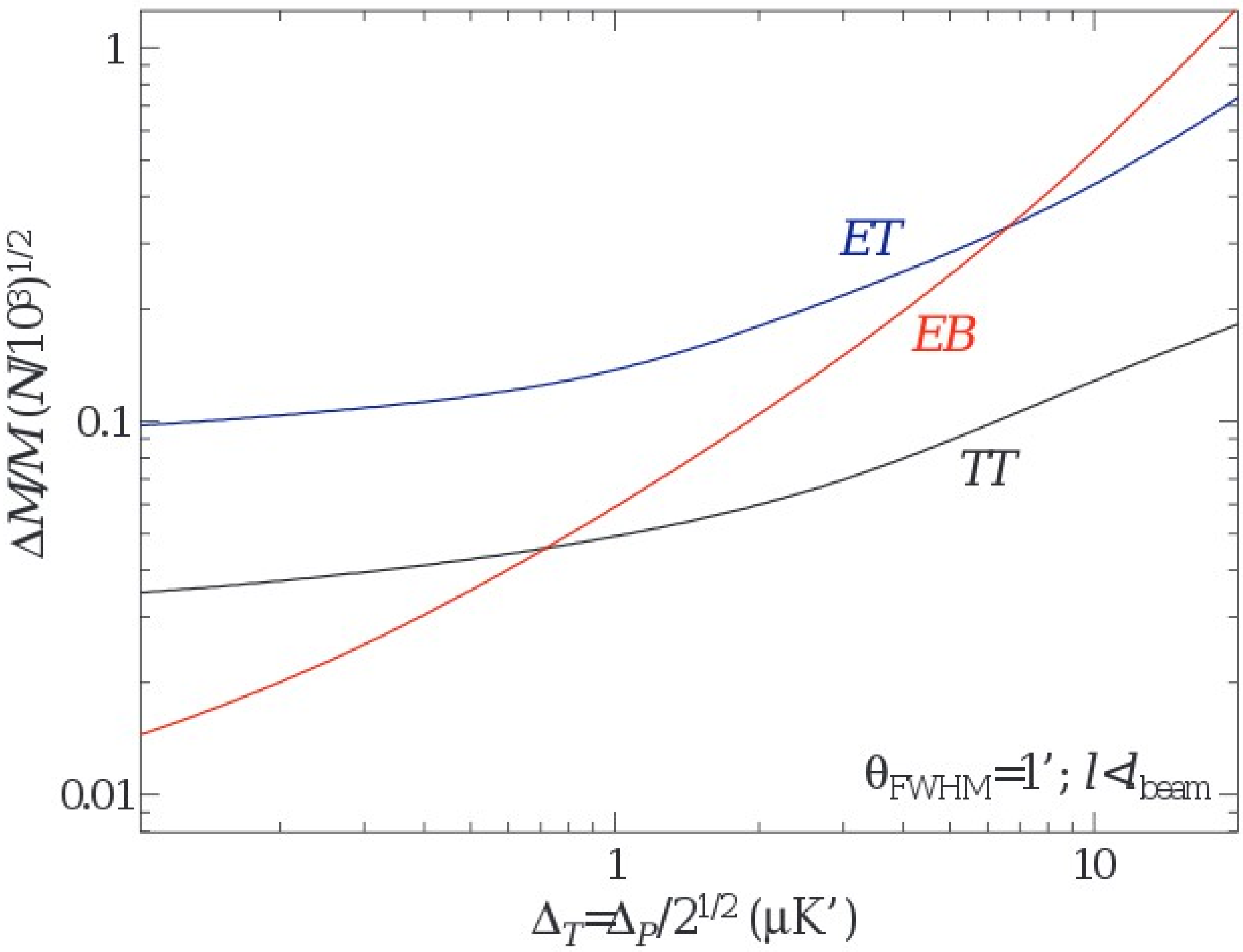
Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1 - b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1 - b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1 - b)$	0.99 ± 0.19
Baseline 2013	$1 - b$	$0.8\,[-0.1, +0.2]$

Notes. CMB lensing directly measures $1/(1 - b)$, which we implement in our analysis; purely for reference, that constraint translates approximately to $1 - b = 1.01^{+0.24}_{-0.16}$. The last line shows the 2013 baseline — a reference model defined by $1 - b = 0.8$ with a flat prior in the $[0.7, 1]$ range.

Planck 2015 XXIV

See also Yin-Zhe Ma et. al., thermalSZxWL, arxiv 2014, 1-b~0.8

Future sensitivities



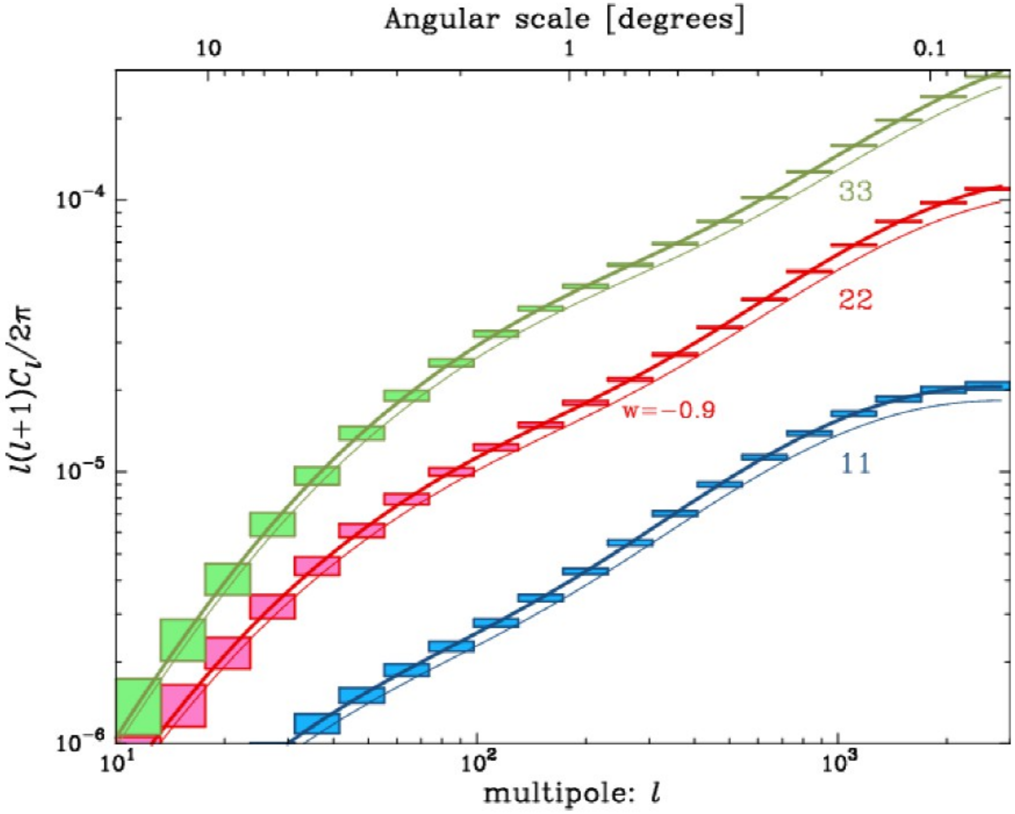
Good rule of thumb is 10% sensitivity per 1000 clusters at current noise levels

Hu, DeDeo, Vale 2007

Cross-correlations

Cross-correlations

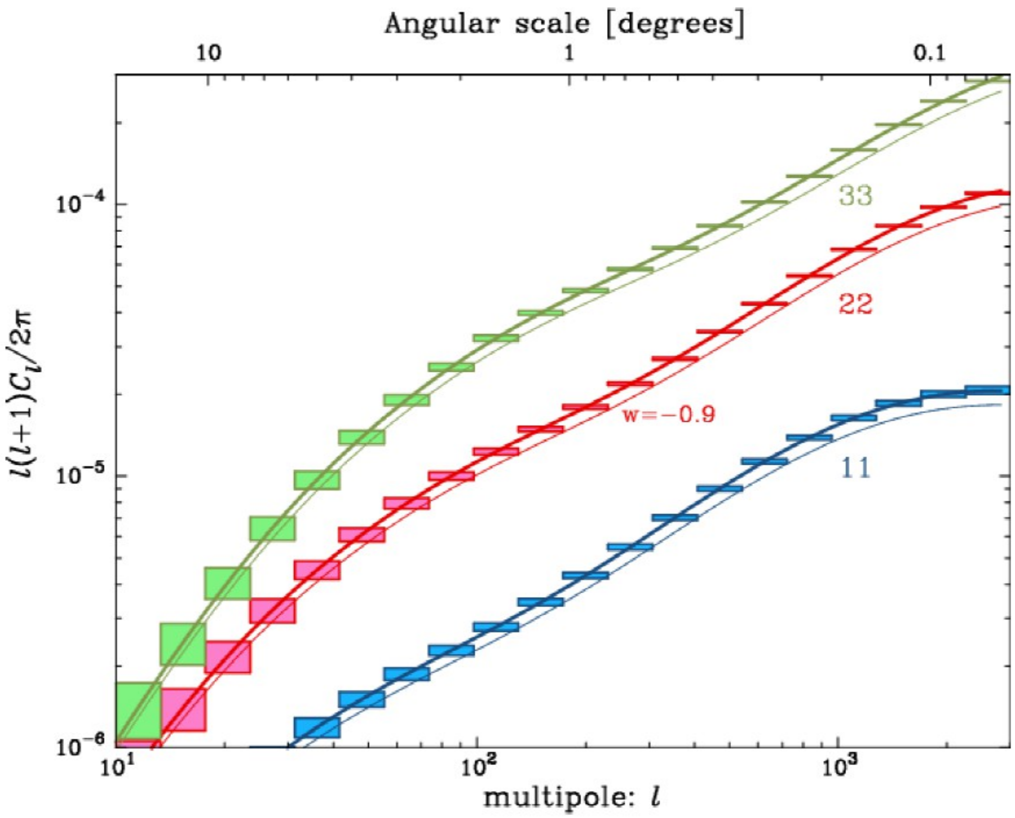
What are they good for?



- Cross-correlate either lensing or tracer samples at different redshifts
  - Probe projected matter density as a function of redshift to reconstruct growth function

Cross-correlations

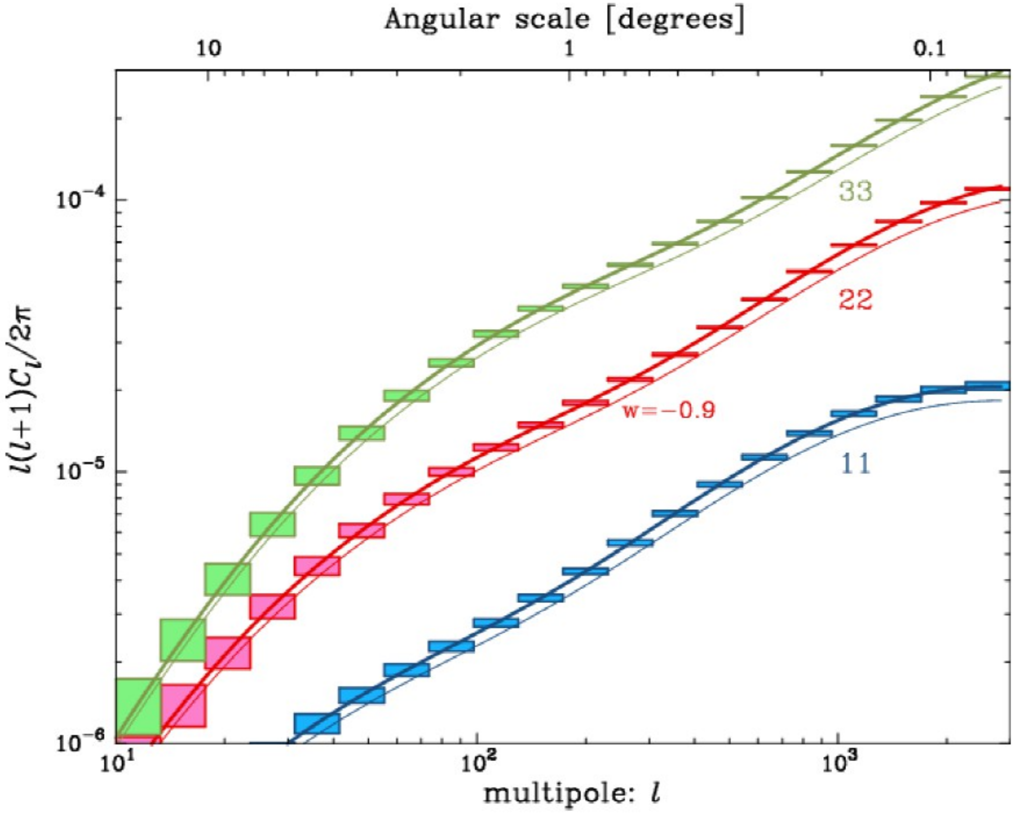
Galaxy Number Counts



- Use galaxy number density?
  - High S/N (lots of galaxies!)
  - But galaxies are biased tracers of underlying matter distribution (additional parameter(s))

Cross-correlations

Galaxy Shear



- Use galaxy shape distortions due to lensing?
  - Directly probes total matter distribution
  - But shapes are noisy
  - And systematic uncertainties (noise bias*, model bias, selection bias) lead to an overall multiplicative bias

* see for e.g. MM, P. McDonald, N. Sehgal, A. Slosar, JCAP, 2015

Cross-correlations

A Way Out: Calibrate with CMB Lensing

- Galaxy bias can be determined by cross-correlating with CMB lensing
  - Degenerate with σ_8, but can be broken by combining with galaxy auto spectrum ~ b^2
- Multiplicative bias can be determined by ratios of cross-correlations with narrow galaxy sample

$$\frac{C_l^{\kappa_1 \delta_f}}{C_l^{\kappa_2 \delta_f}} = \frac{m_1}{m_2} \frac{g_1(z_f)}{g_2(z_f)}$$

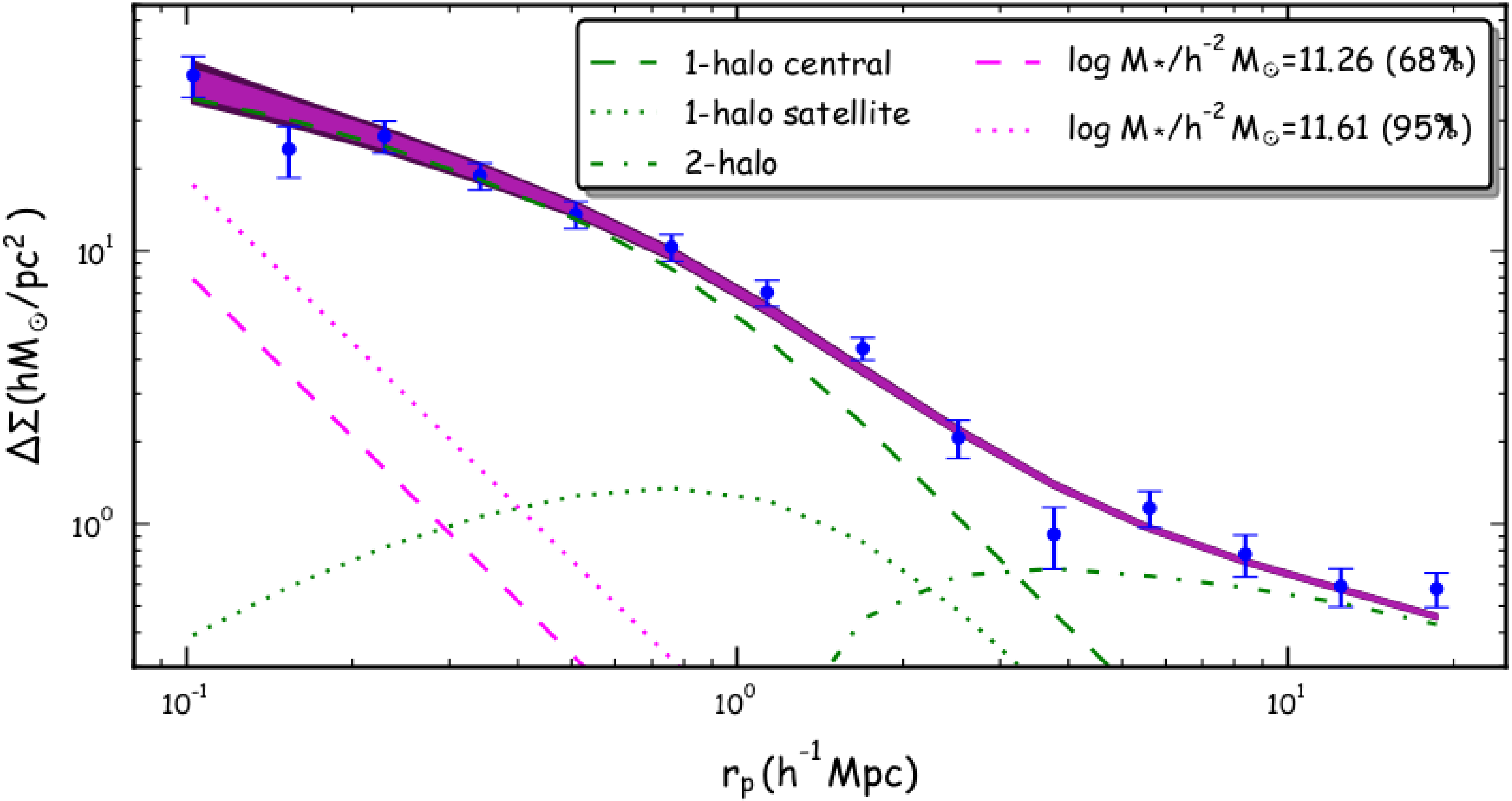
Das, Errard, Spergel, 2013

Some prelim slides removed

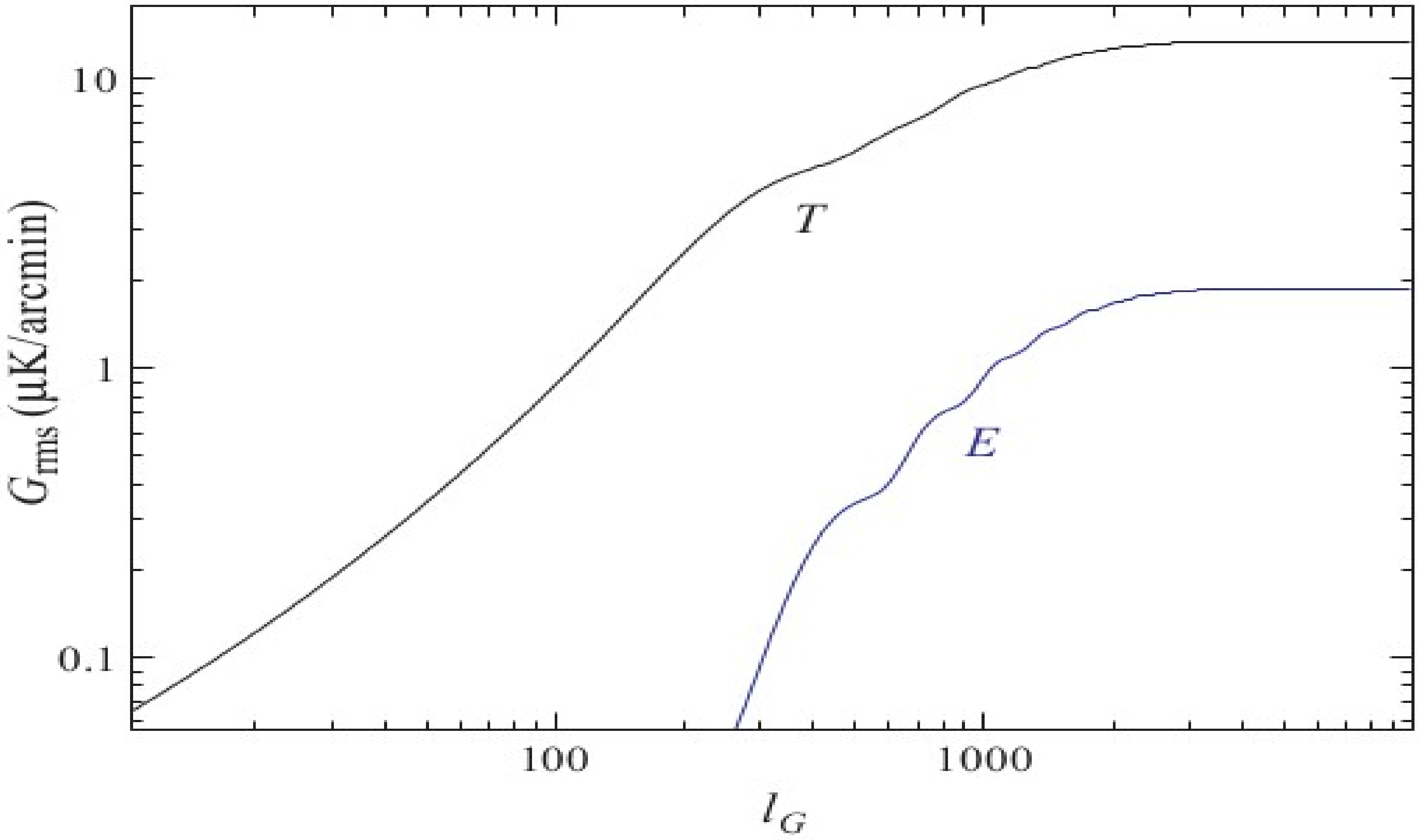
Summary

- Clean measurements of cluster masses crucial for constraining dark energy parameters
- Lensing probes total mass; CMB as a backlight offers complementary probe to optical WL
- ACTPol has demonstrated a 3.2σ detection of CMB halo lensing with galaxy groups; SPTPol/Planck reported/reporting cluster measurements
- Cross-correlations with CMB Lensing can be used to tomographically probe growth and constrain biases in optical weak lensing data

Bonus Slides: Miyatake et. al. 2013

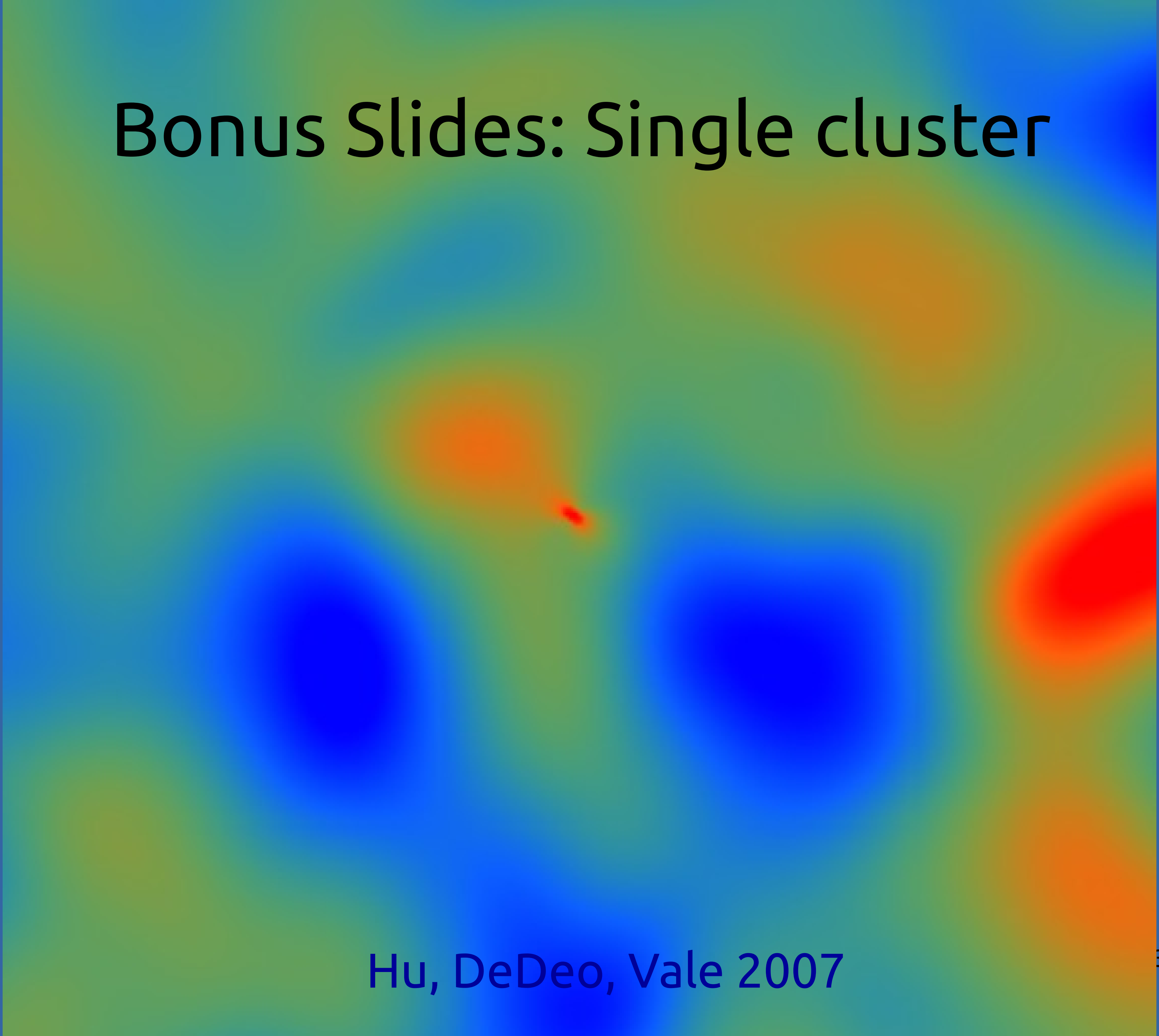


Bonus Slides: Gradient cutoff



Hu, DeDeo, Vale 2007

Bonus Slides: Single cluster



Hu, DeDeo, Vale 2007